NA61 incident pion for PPFX

$$\boxed{\text{pi} + \text{C} \rightarrow \text{pi} + \text{X}}$$

Nilay Bostan (UIowa)

For PPFX group meeting

Feb 19/2021

Introduction

- **Fine interpolation of the data (θ, P):**

1) We use a covariance matrix to generate "many universes".

2) We assume 50% correlation.

3) We make the integral preserving interpolation technique which was implemented by Antoni. We do these each universe.

- **Making PPFX input:**

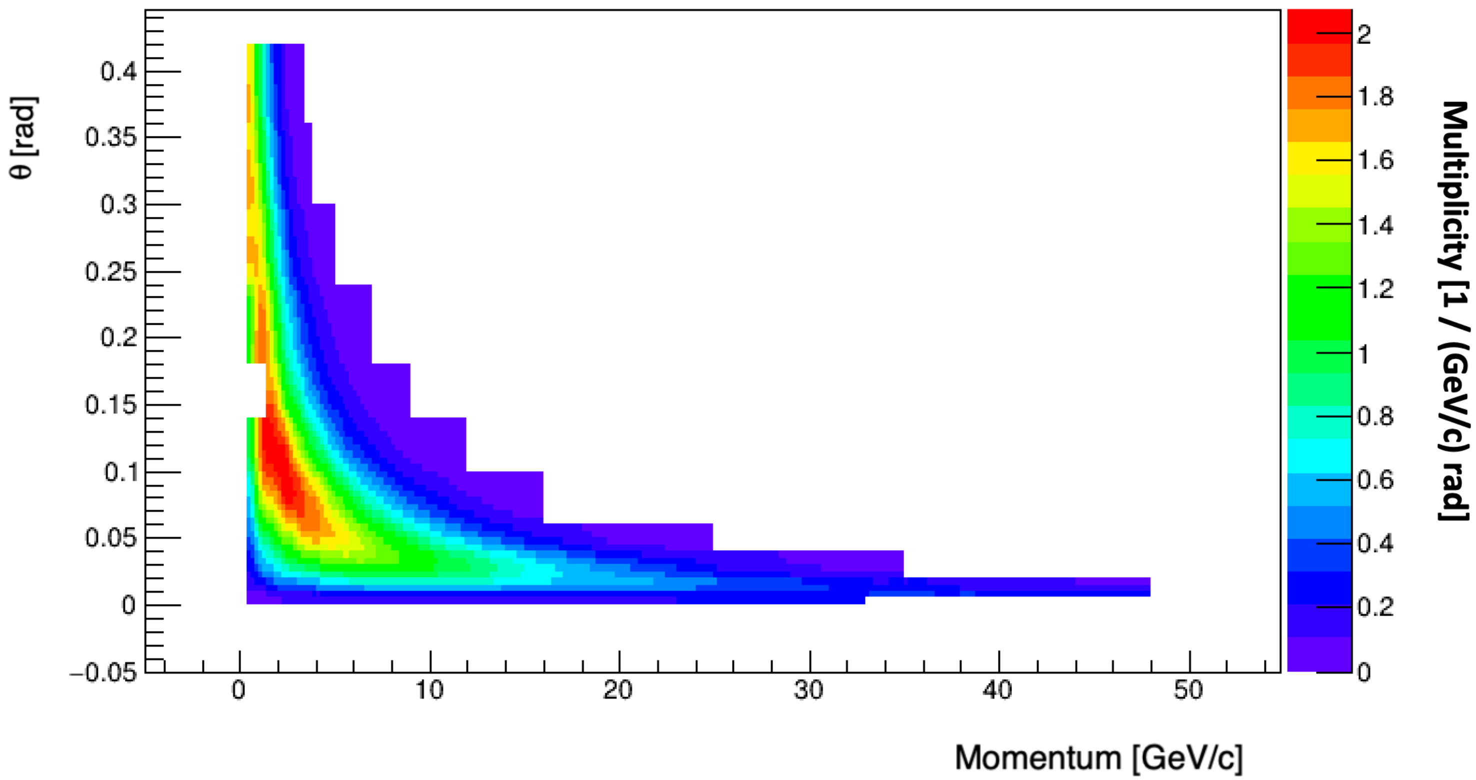
1) The generation of MC cross-section for incident pions on carbon for energies: 12, 16, 20, 25, 30, 35, 40, 45, 50, 55, 60, 100 GeV has been completed (for QGSP_BERT and FTFP_BERT).

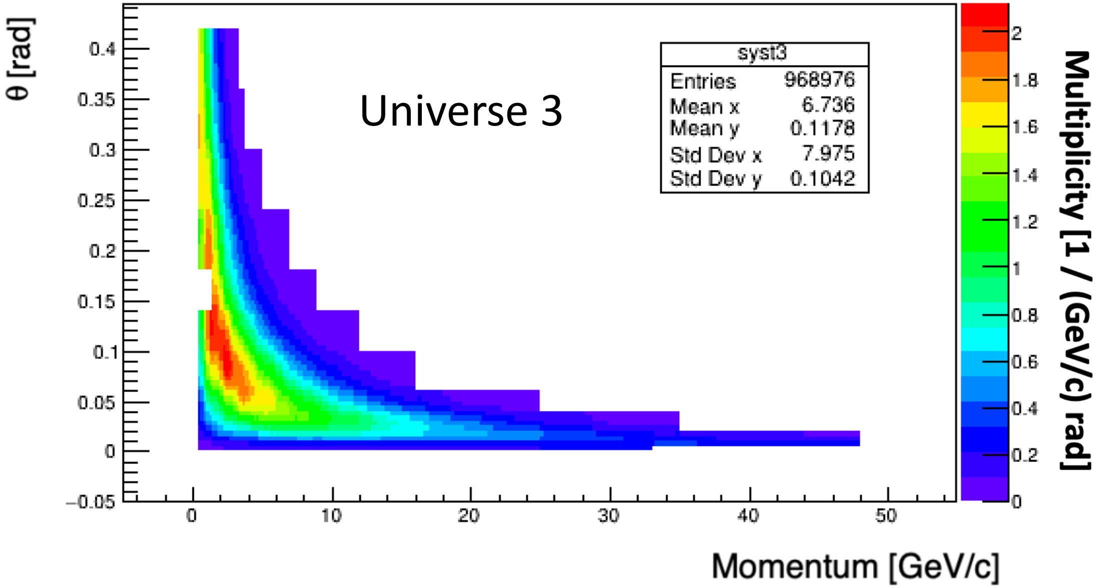
2) Working to calculate <f(xf,pt)> from n(P, θ).

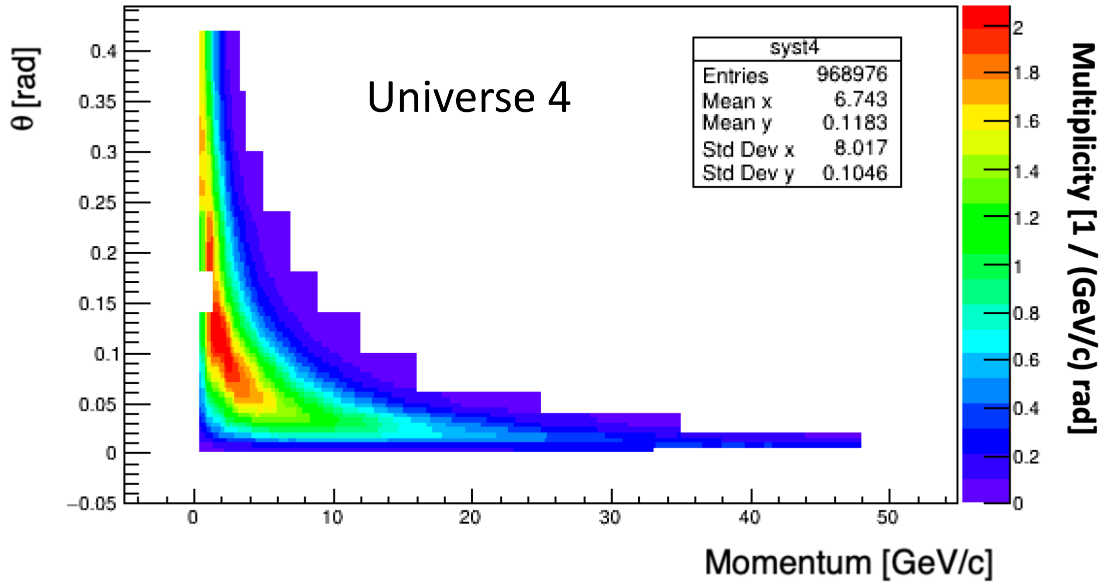
3) We will use Feynman scaling to go from 60 GeV to 12-60 GeV.

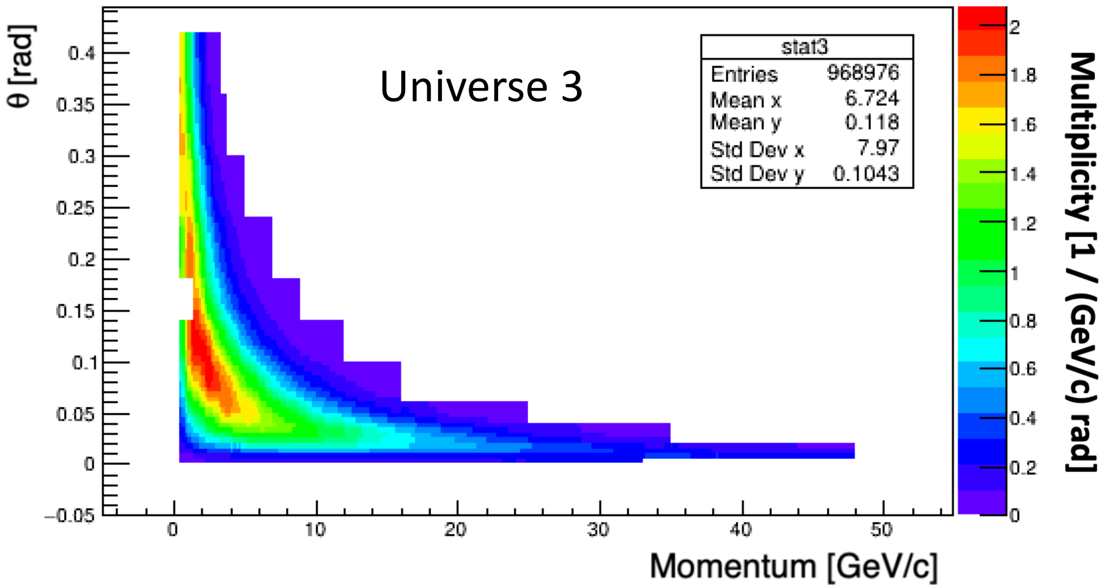
4) We will use FLUKA to correct any scaling violation.

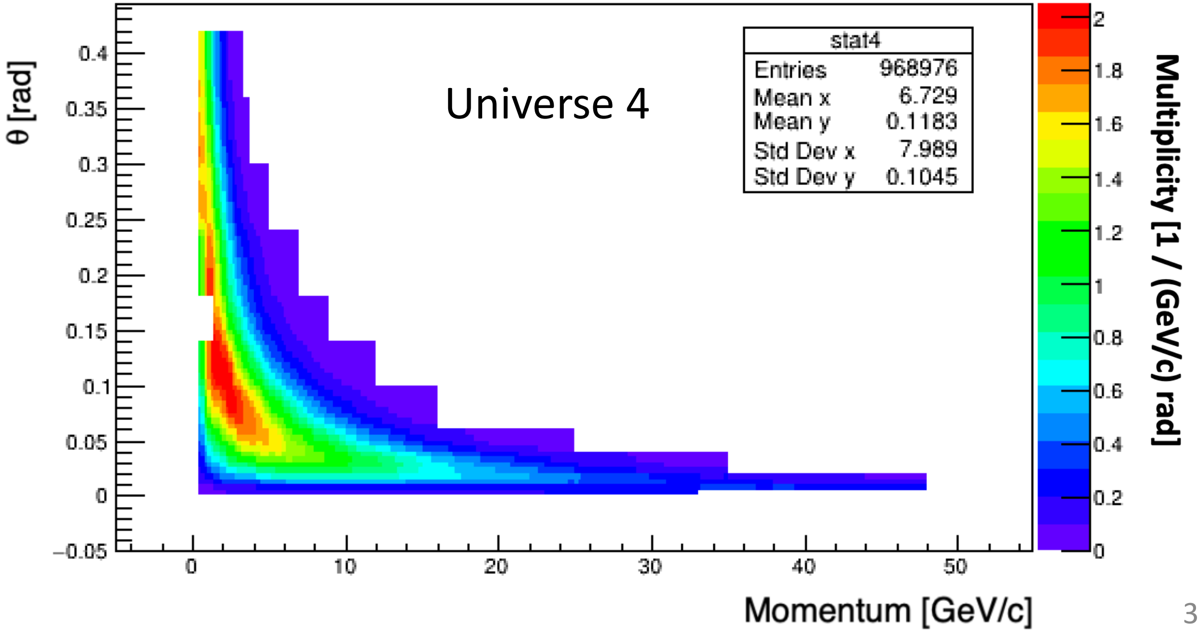
interpolated NA61 CV data



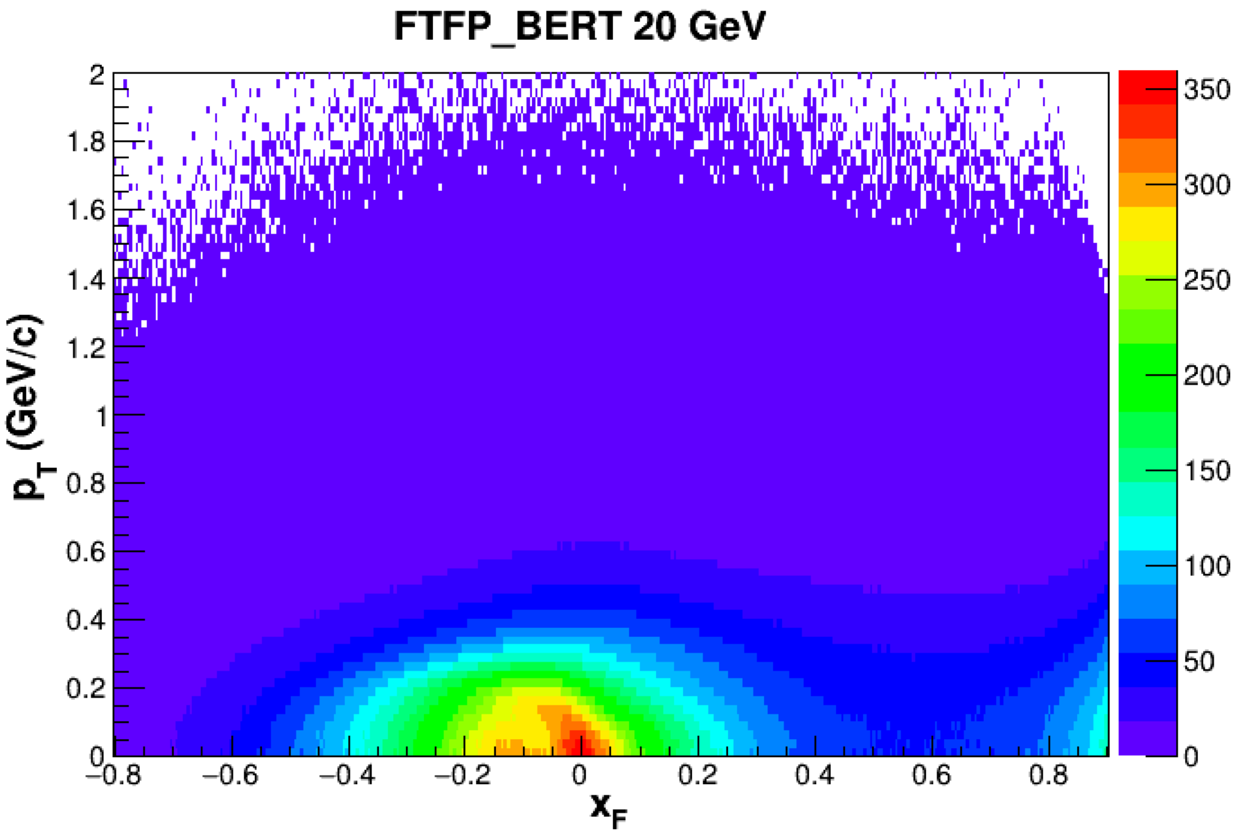

Universe 3
syst3
Entries 968976
Mean x 6.736
Mean y 0.1178
Std Dev x 7.975
Std Dev y 0.1042
θ [rad]
Momentum [GeV/c]
Multiplicity [1 / (GeV/c) rad]

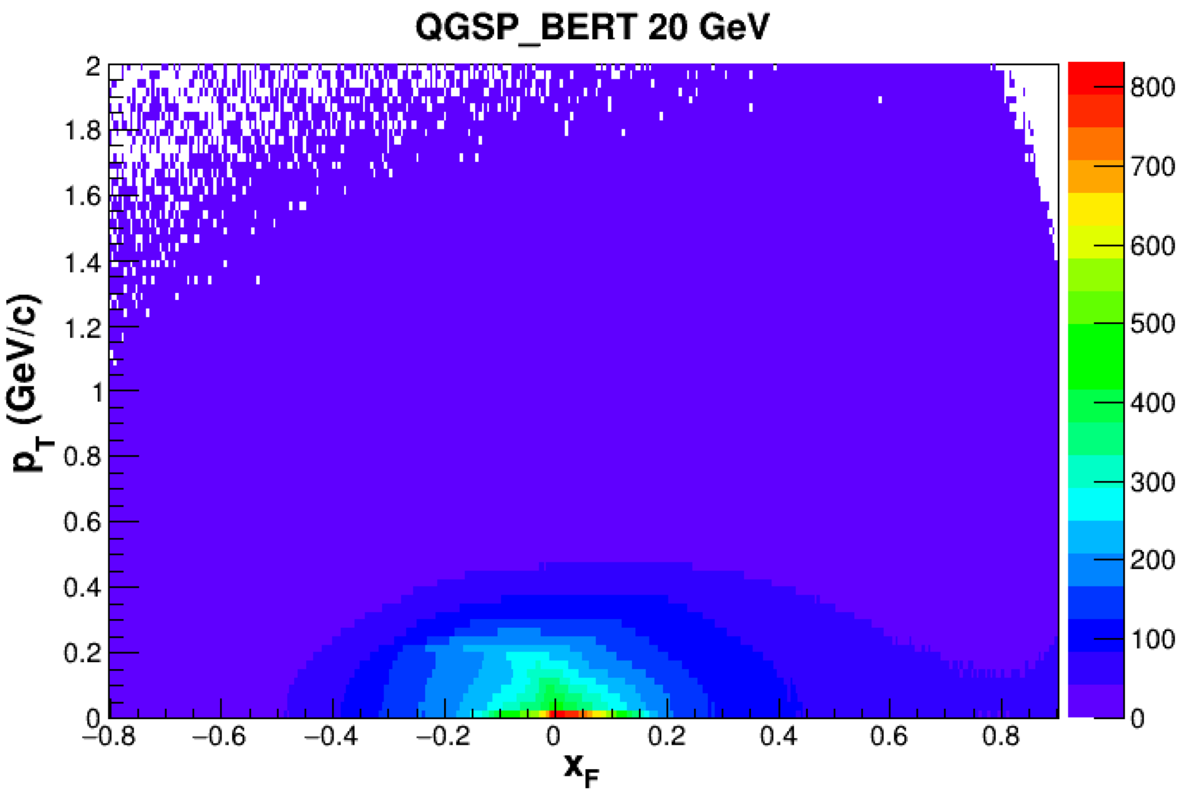

Universe 4
syst4
Entries 968976
Mean x 6.743
Mean y 0.1183
Std Dev x 8.017
Std Dev y 0.1046
θ [rad]
Momentum [GeV/c]
Multiplicity [1 / (GeV/c) rad]


Universe 3
stat3
Entries 968976
Mean x 6.724
Mean y 0.118
Std Dev x 7.97
Std Dev y 0.1043
θ [rad]
Momentum [GeV/c]
Multiplicity [1 / (GeV/c) rad]

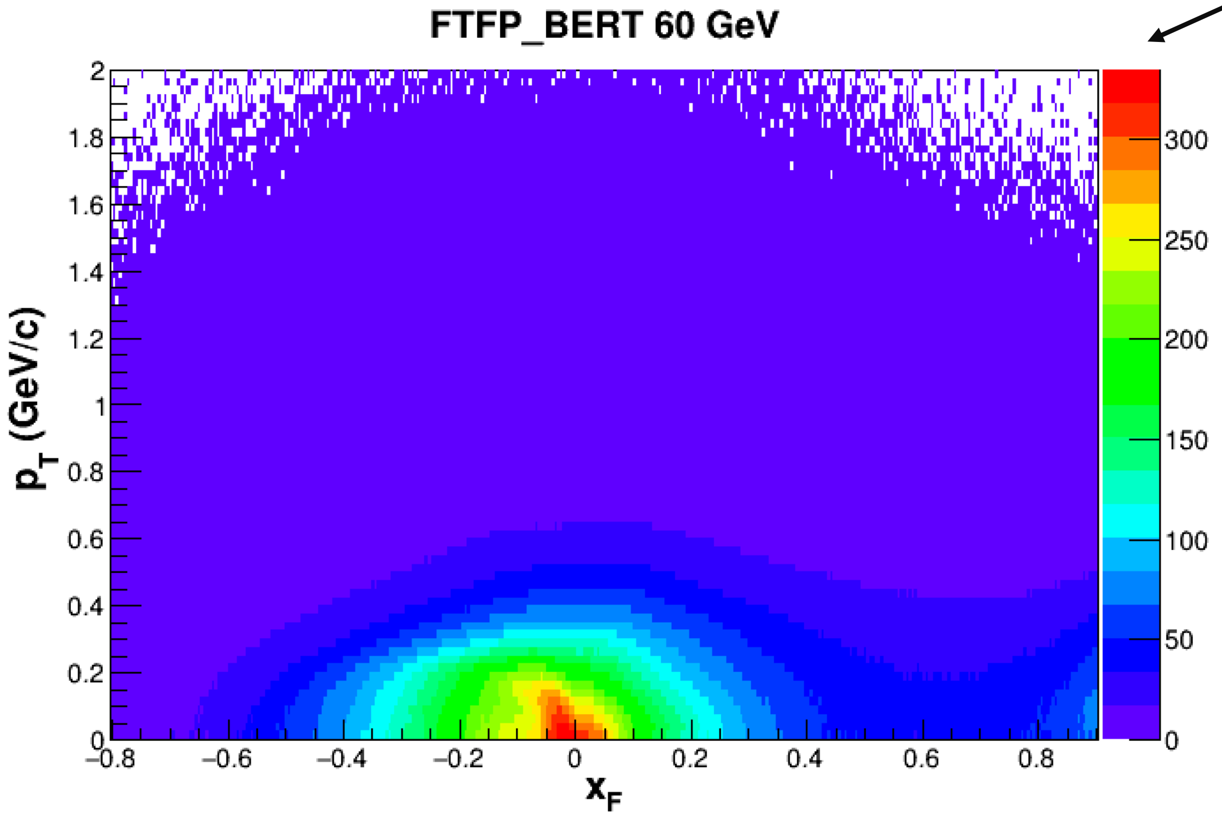

Universe 4
stat4
Entries 968976
Mean x 6.729
Mean y 0.1183
Std Dev x 7.989
Std Dev y 0.1045
θ [rad]
Momentum [GeV/c]
Multiplicity [1 / (GeV/c) rad]

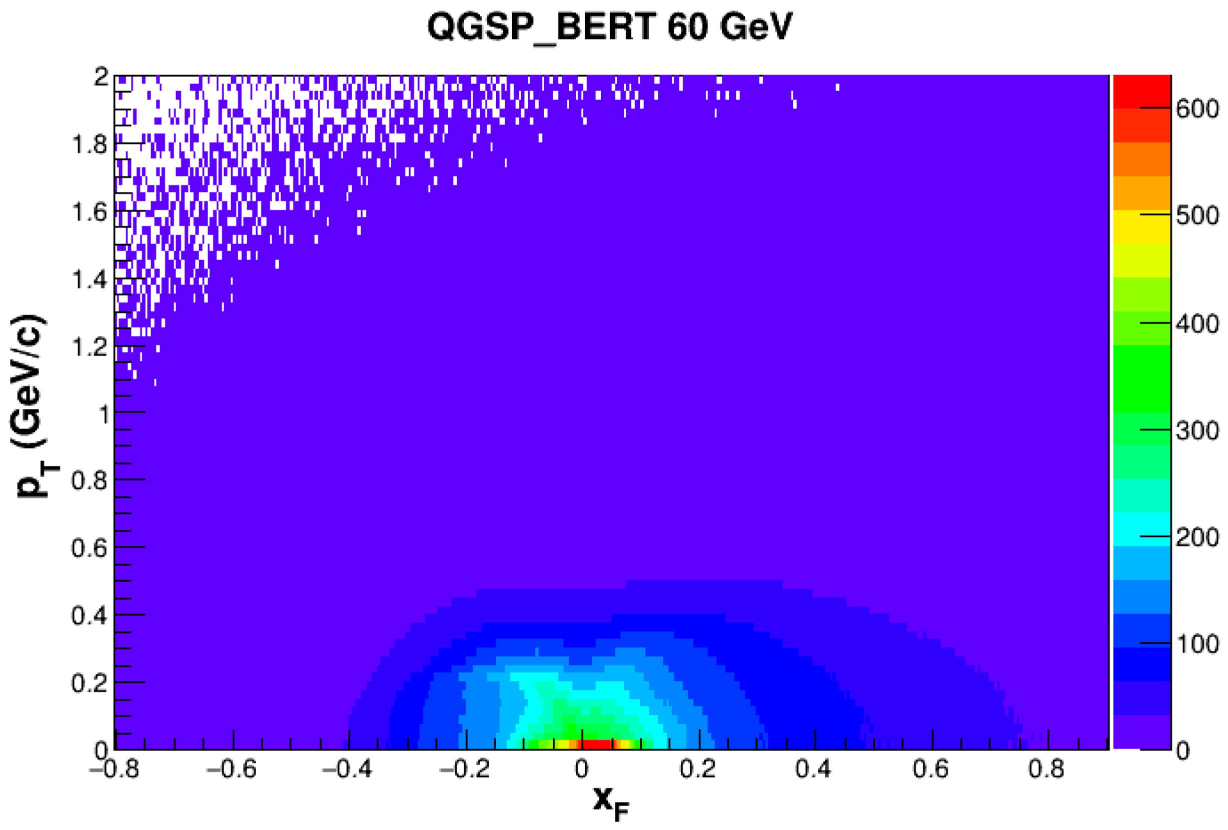
Invariant cross-section for FTFP_BERT and QGSP_BERT for $\boxed{20\ GeV}$





Invariant cross-section for FTFP_BERT and QGSP_BERT for 60 GeV





Conclusions

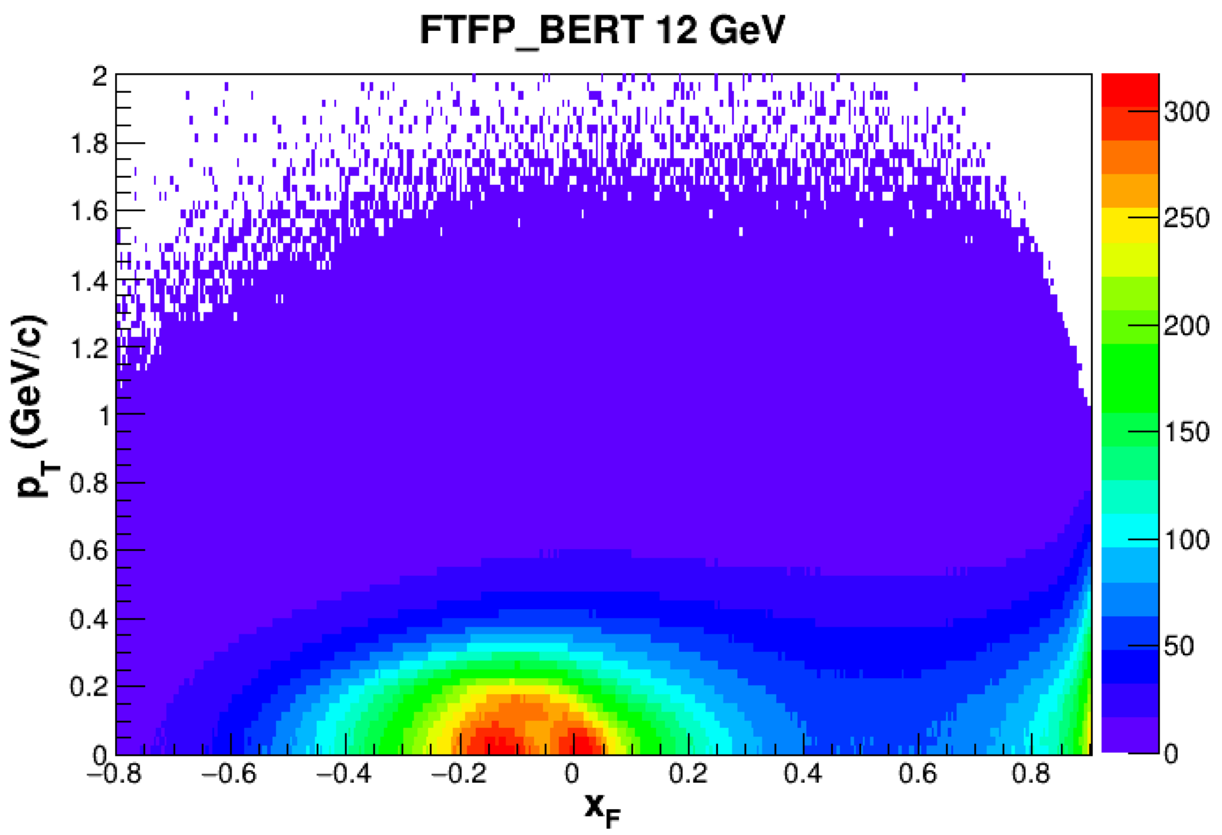
- In this talk, I showed the NA61 60 GeV interpolated data (the integral preserving interpolation technique which was implemented by Antoni).
- The generation of MC cross section for different energies is completed.
- I am working on the PPFX implementation.

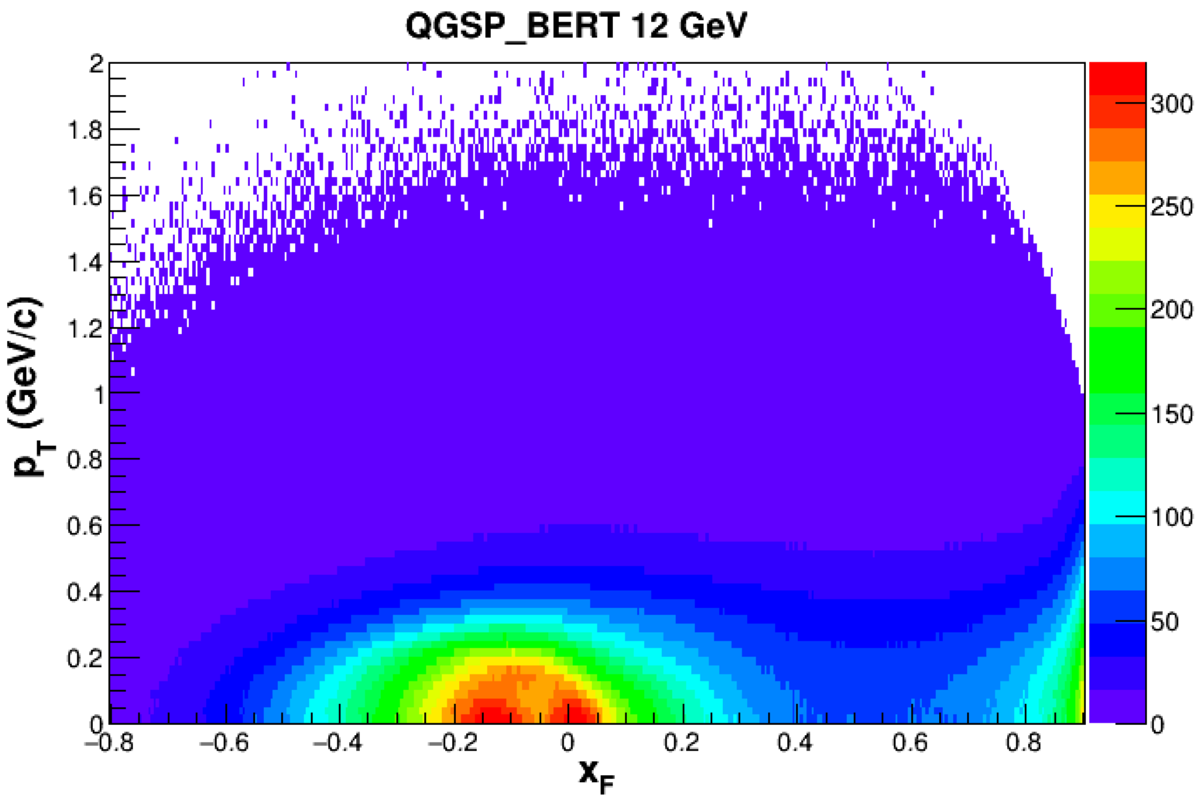
Thank you very much for listening!

Any comments and/or suggestions are welcome!!!

Backup

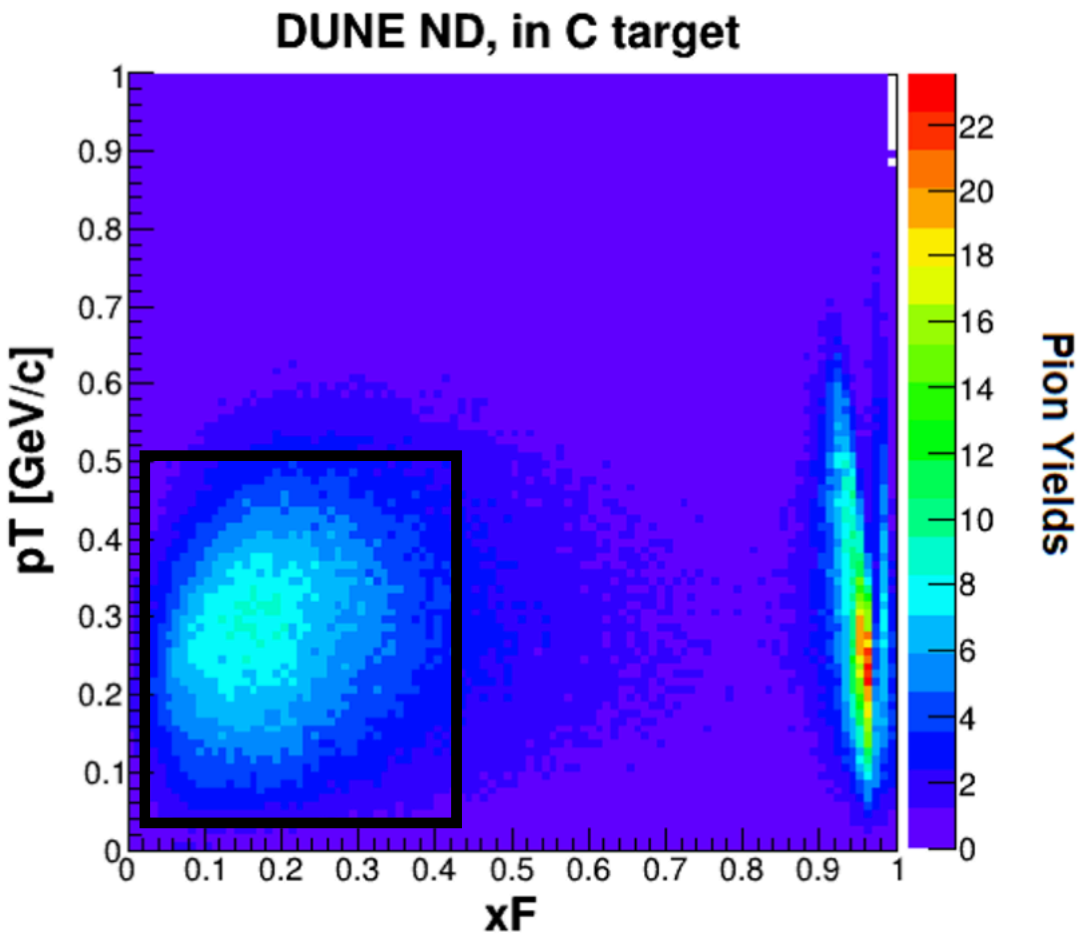
Invariant cross-section for FTFP_BERT and QGSP_BERT for 12 GeV



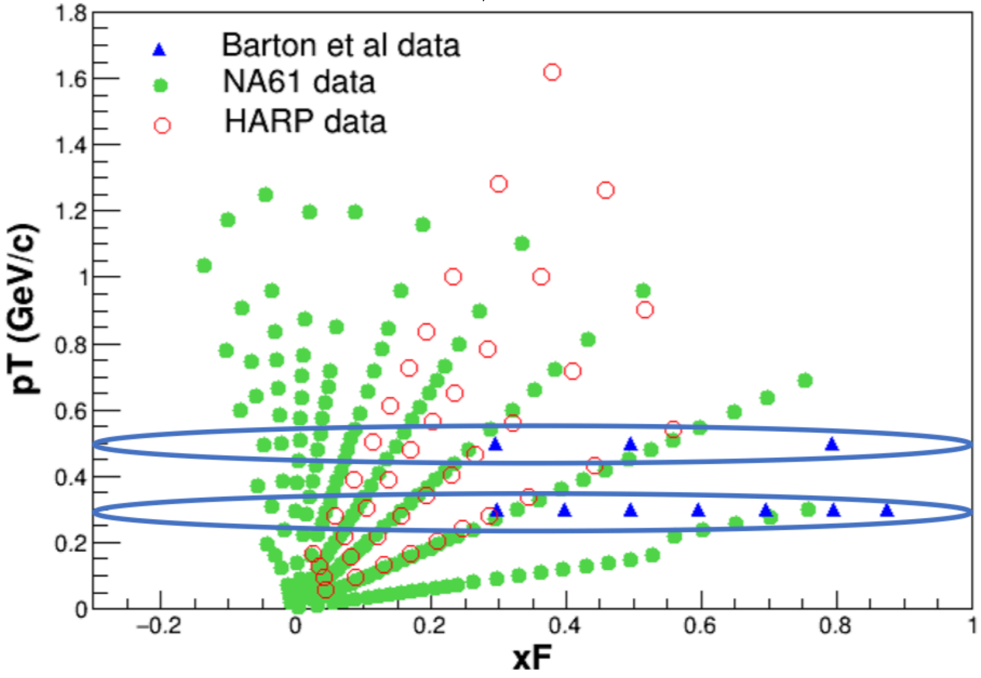


REMINDER SLIDE

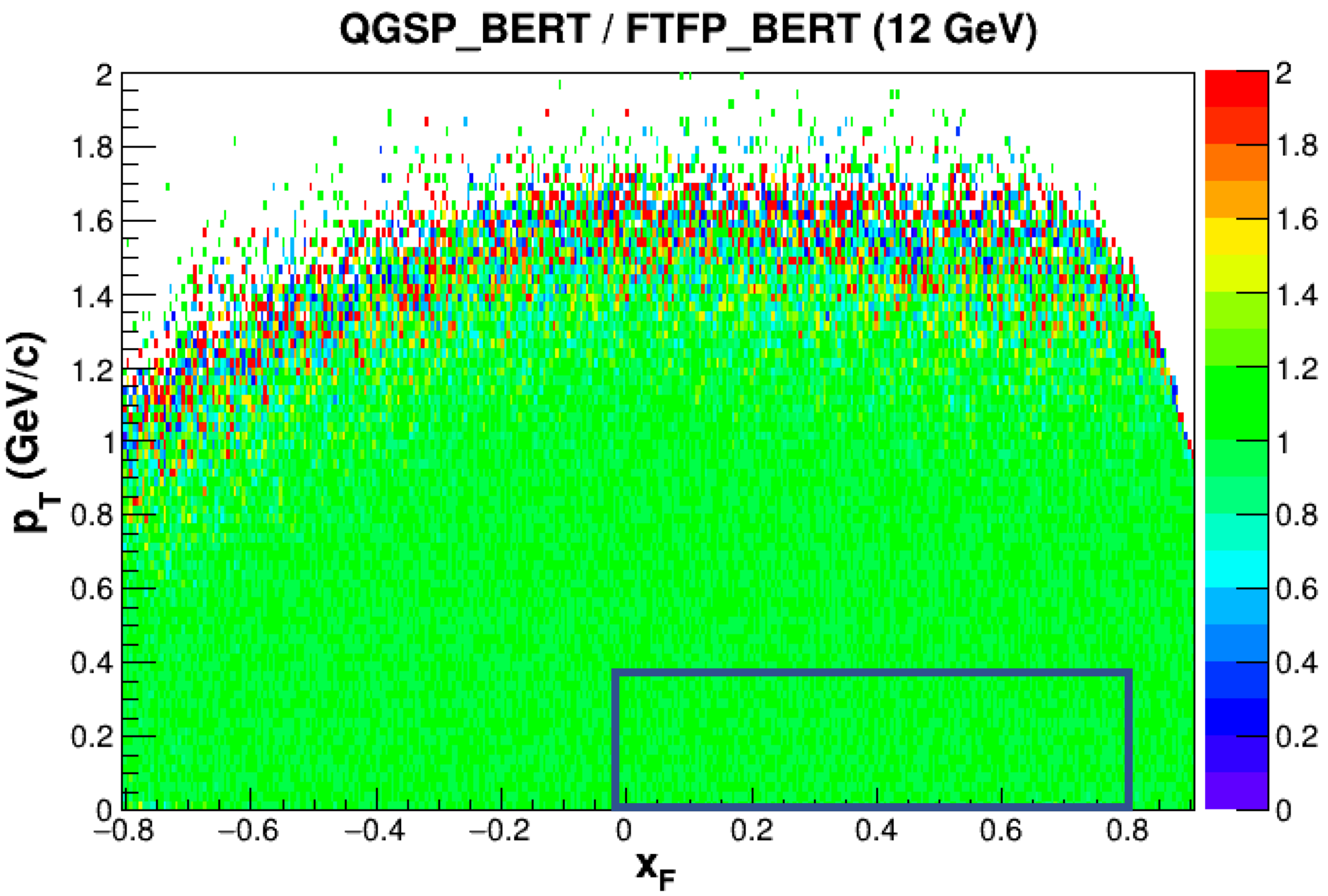
Pion production phase space in C target



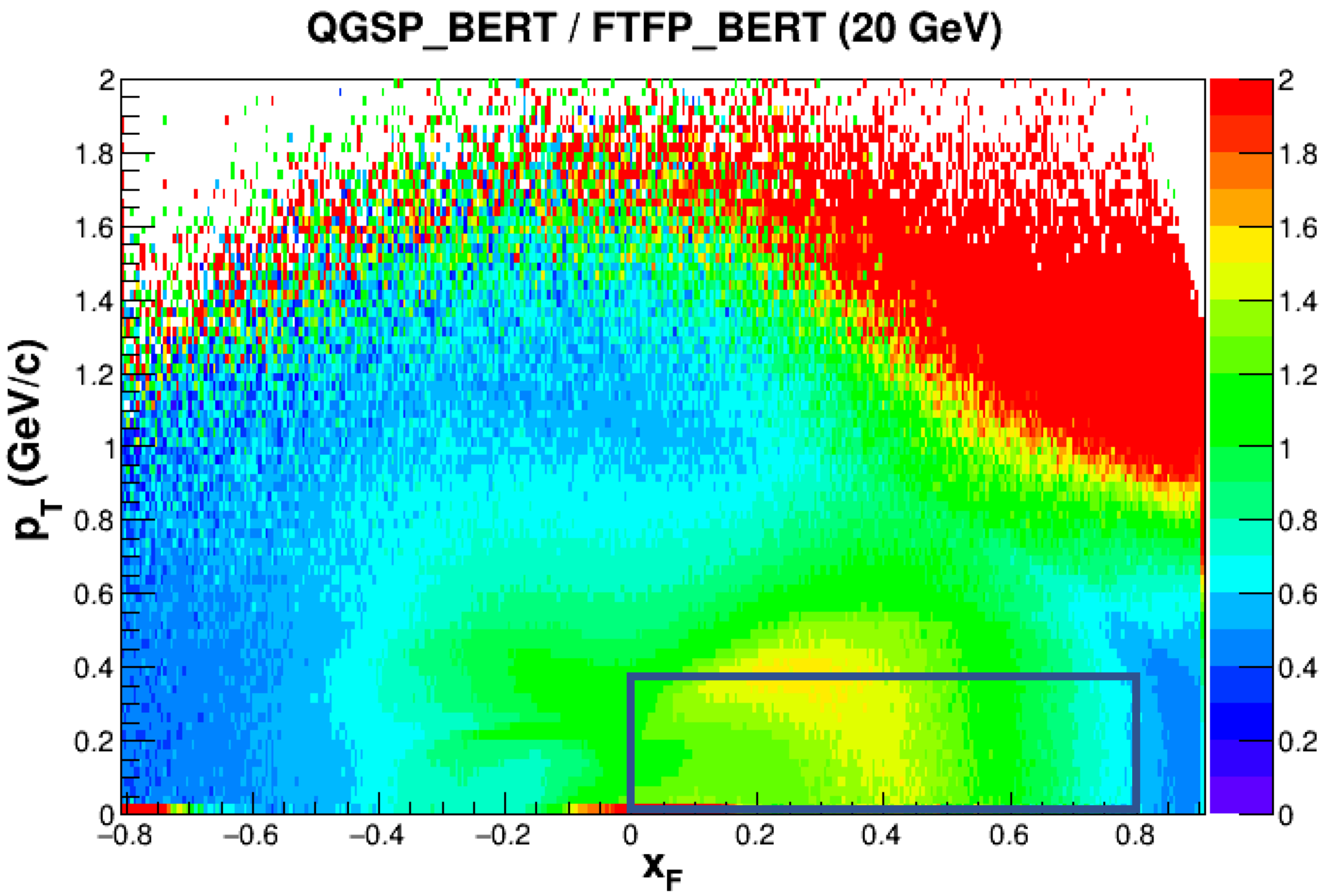
Data coverage



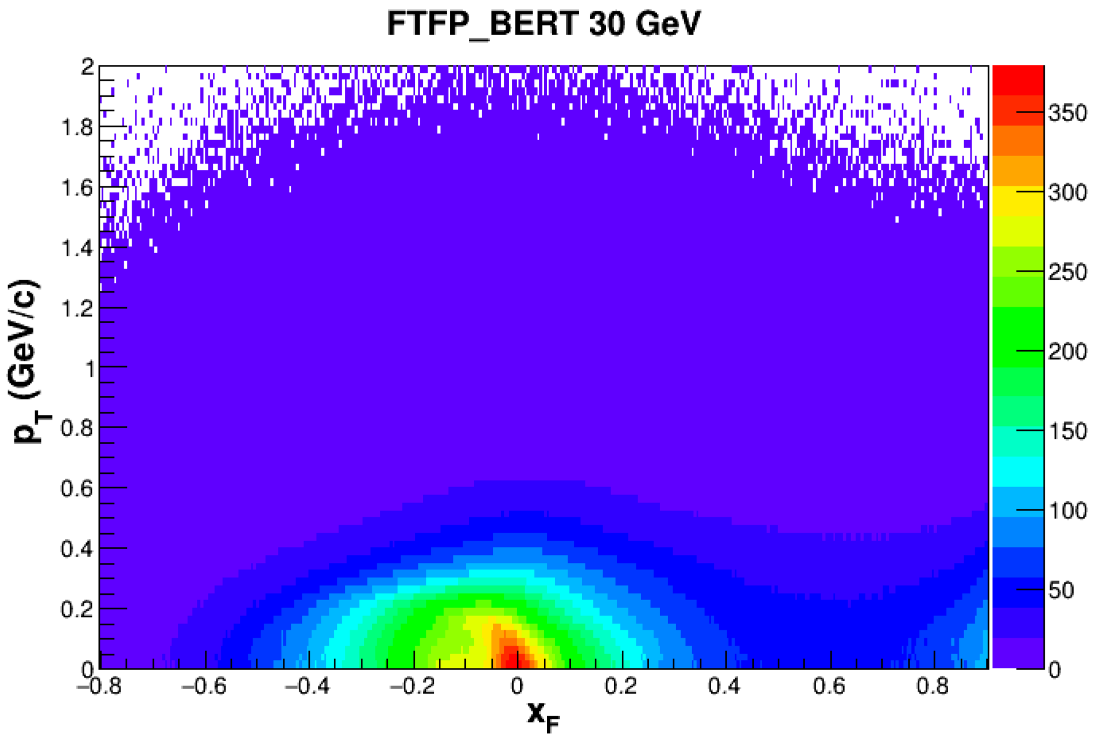
Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 12 GeV

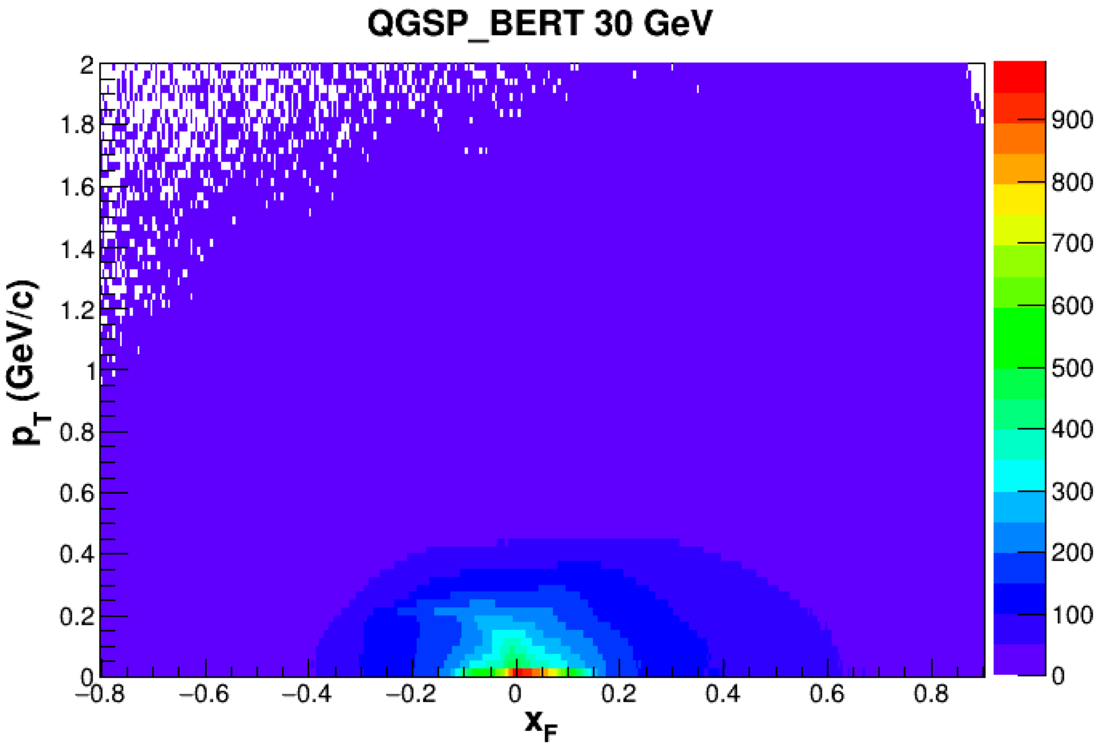


Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 20 GeV

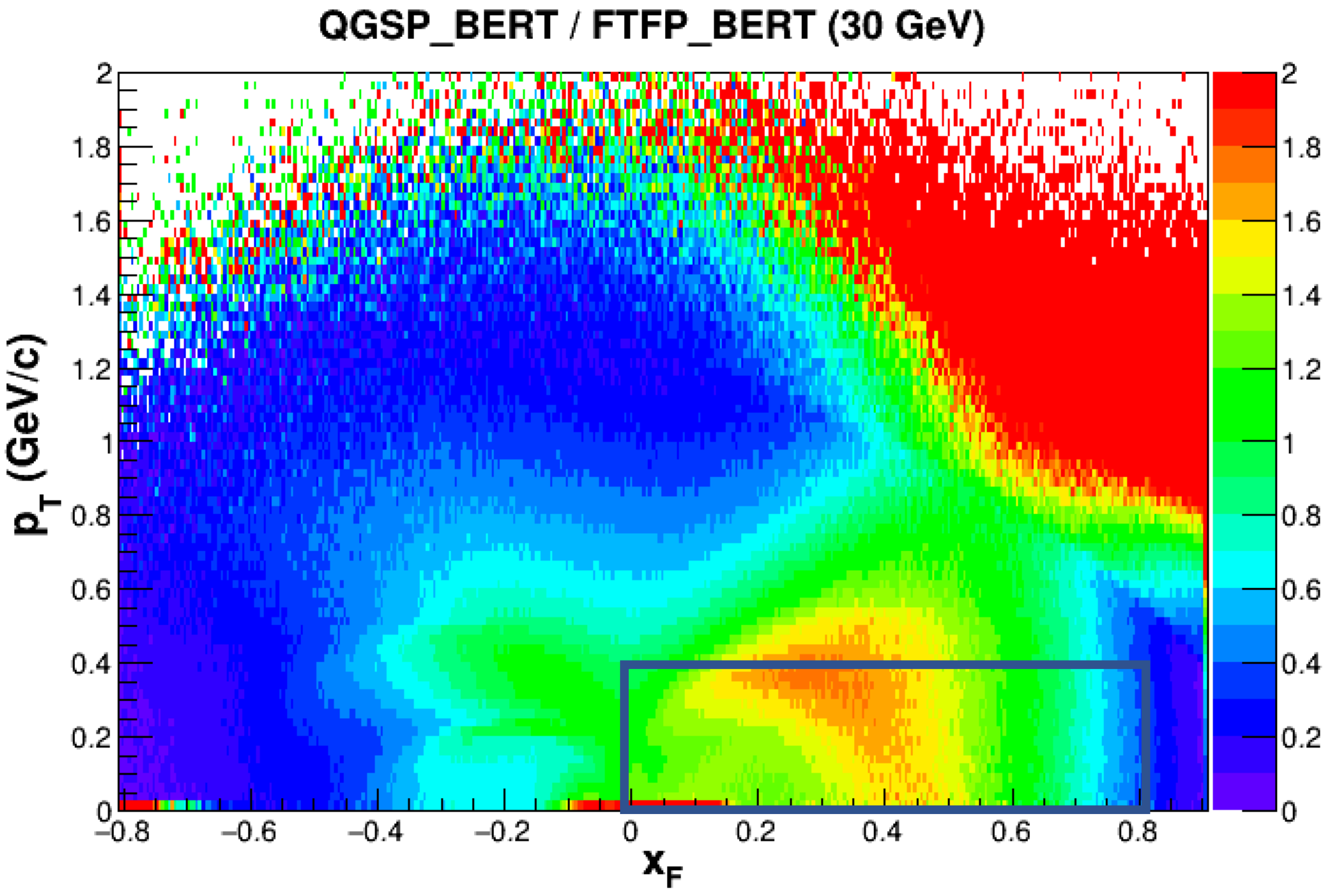


Invariant cross-section for FTFP_BERT and QGSP_BERT for 30 GeV

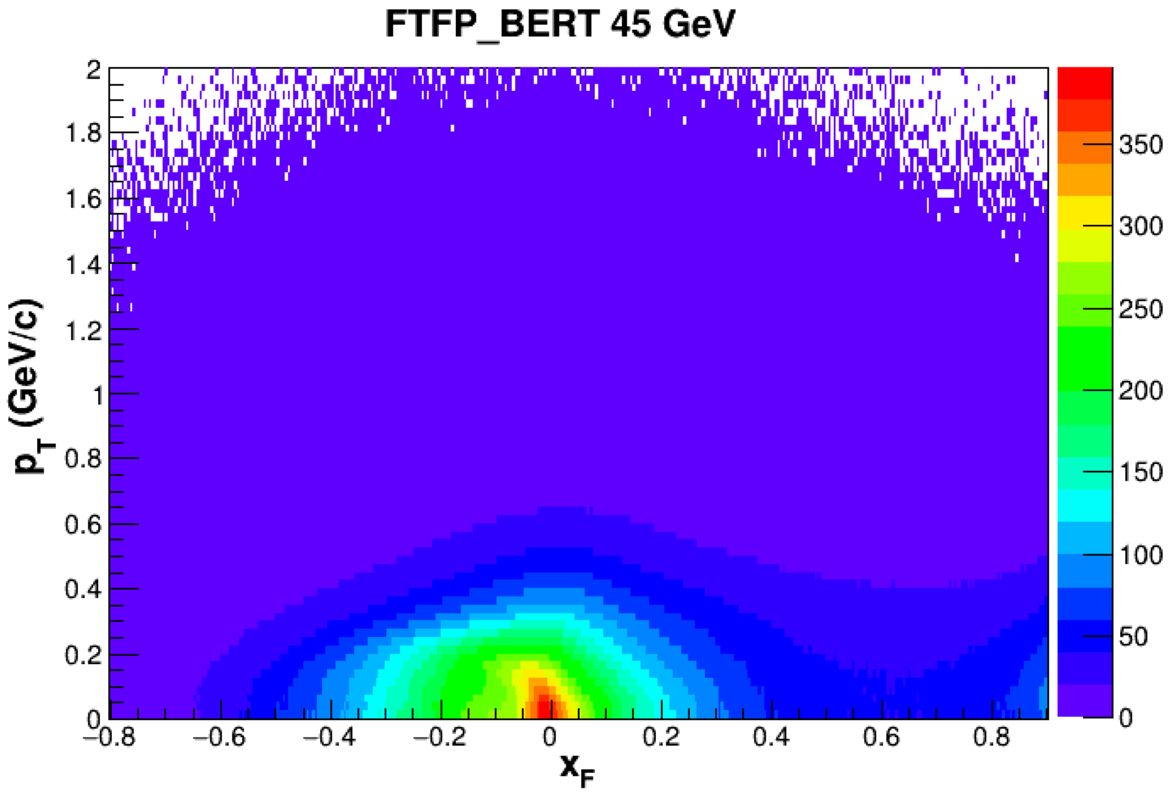


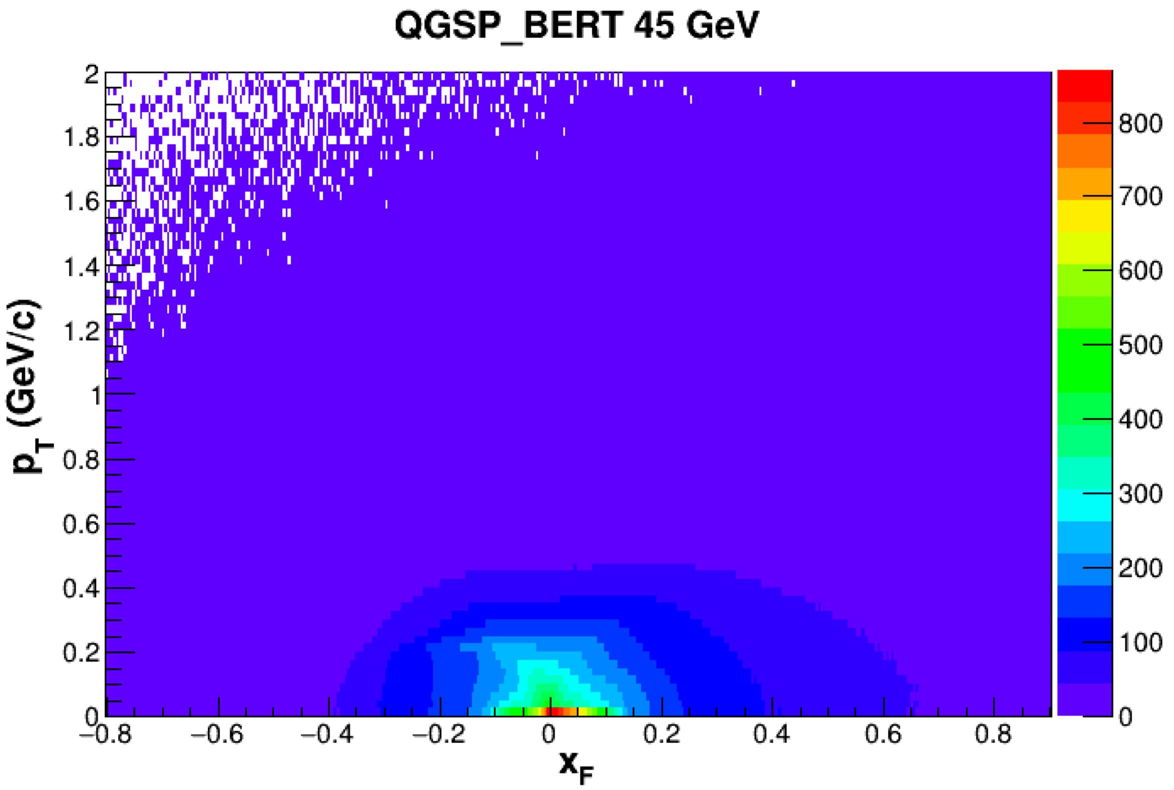


Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 30 GeV

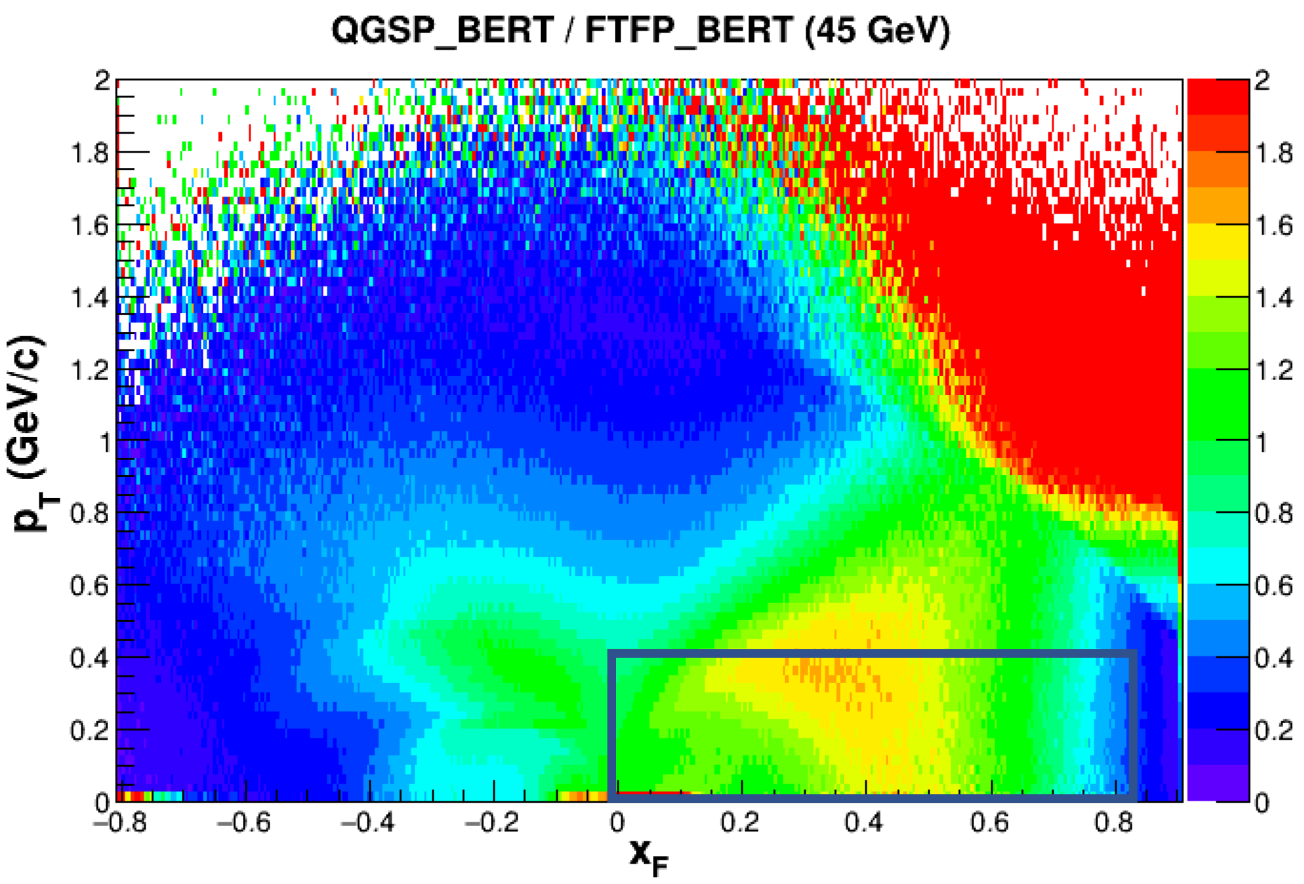


Invariant cross-section for FTFP_BERT and QGSP_BERT for 45 GeV

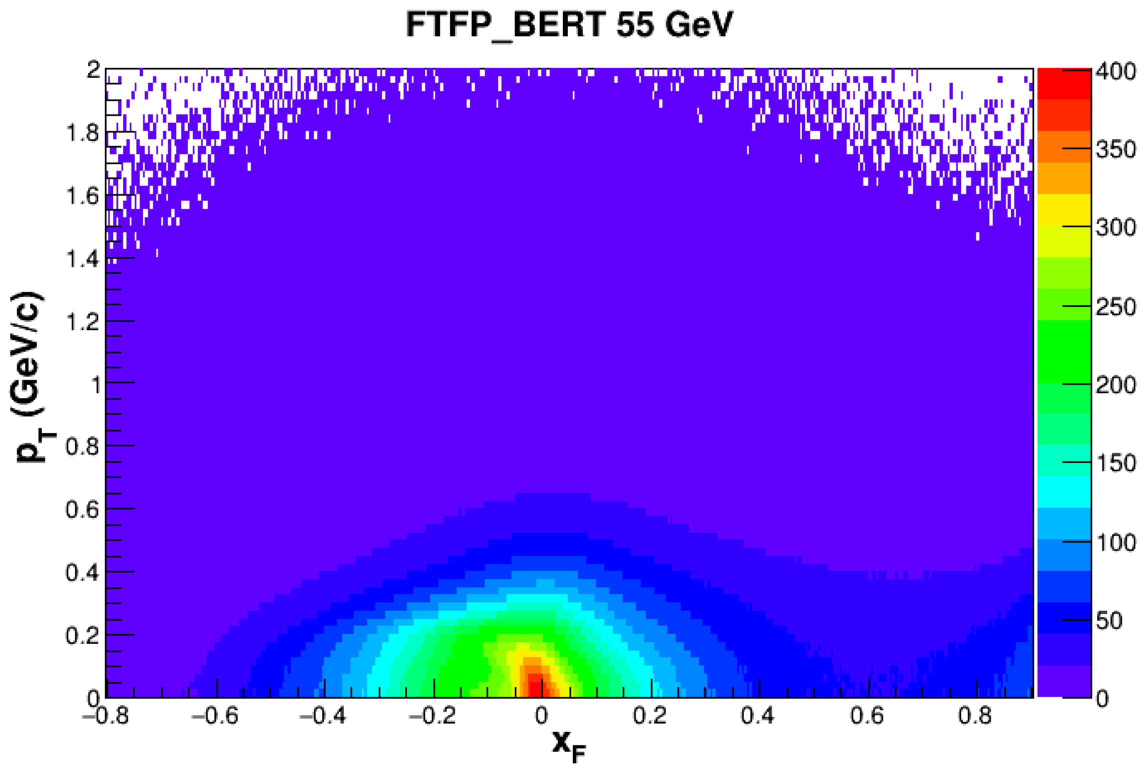


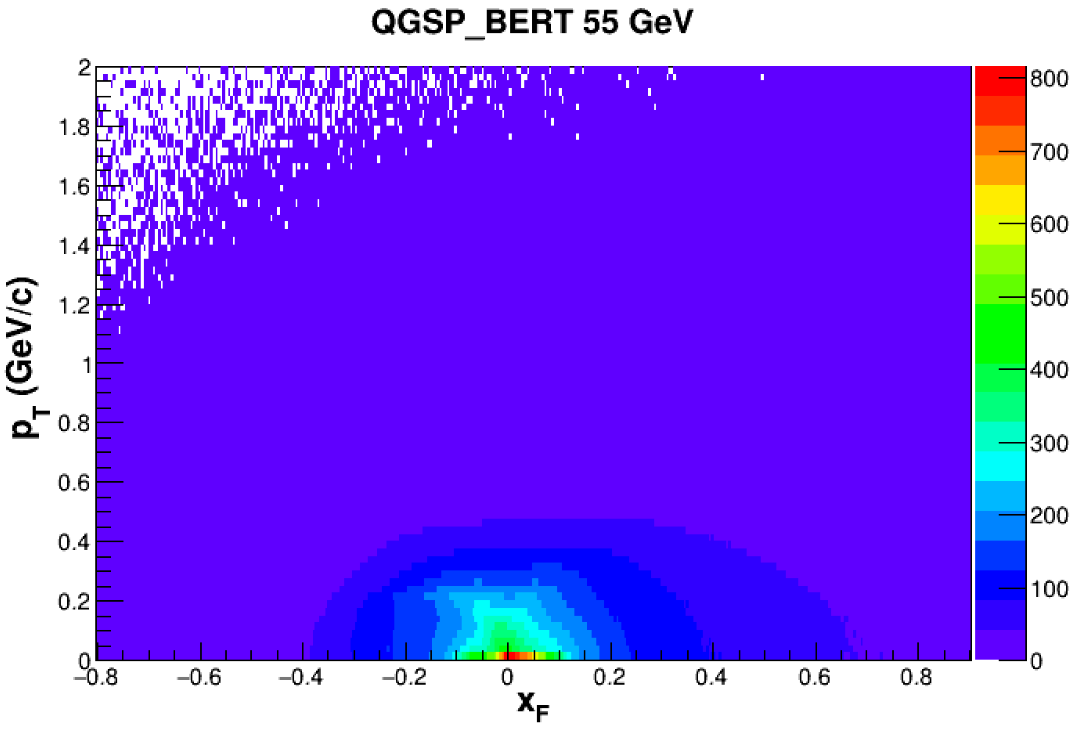


Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 45 GeV

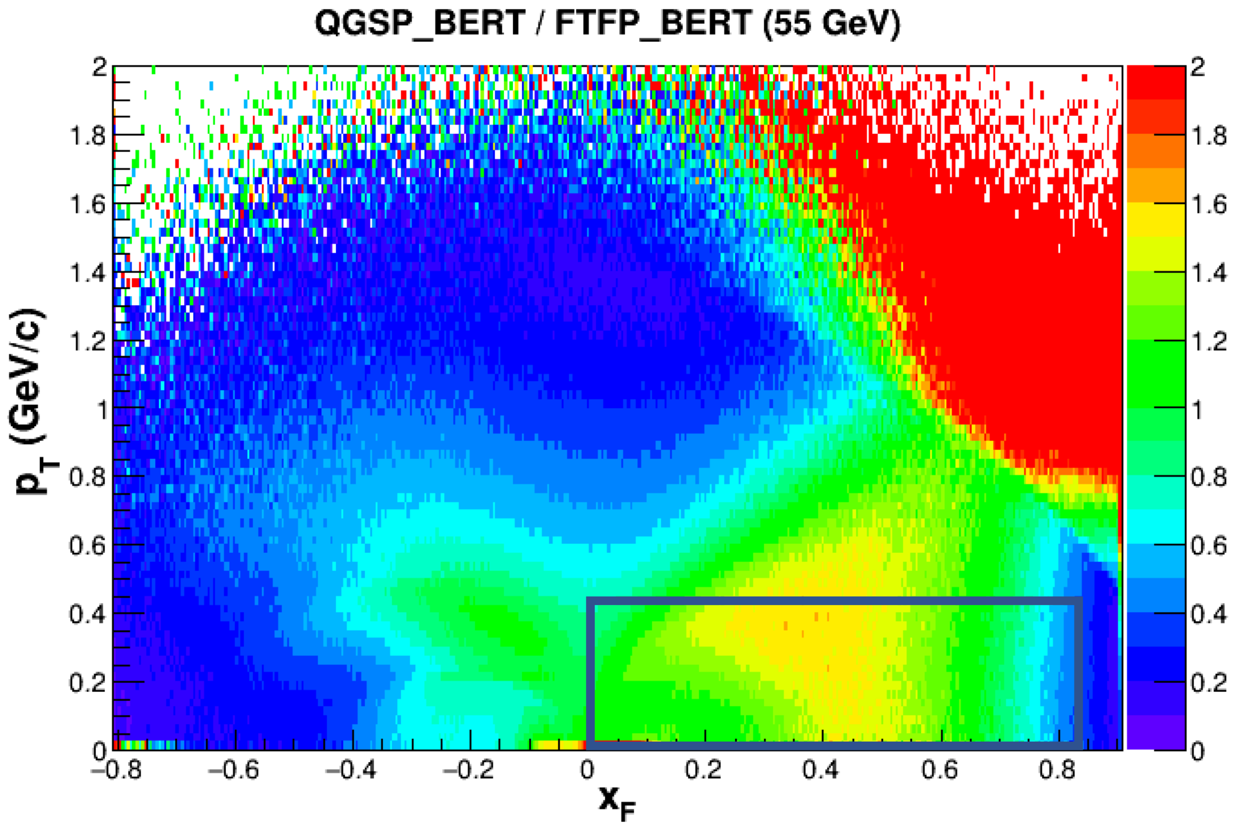


Invariant cross-section for FTFP_BERT and QGSP_BERT for 55 GeV

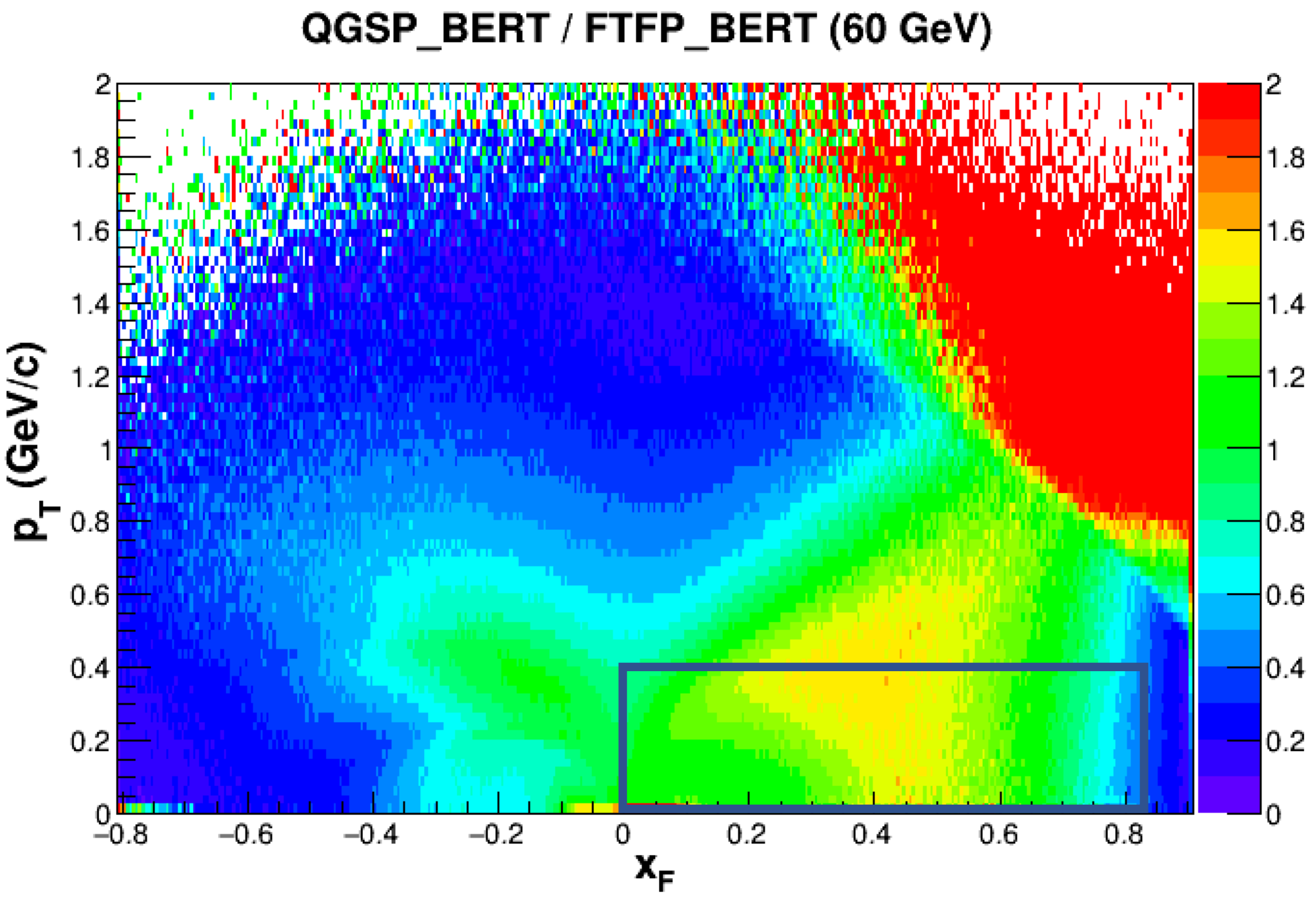




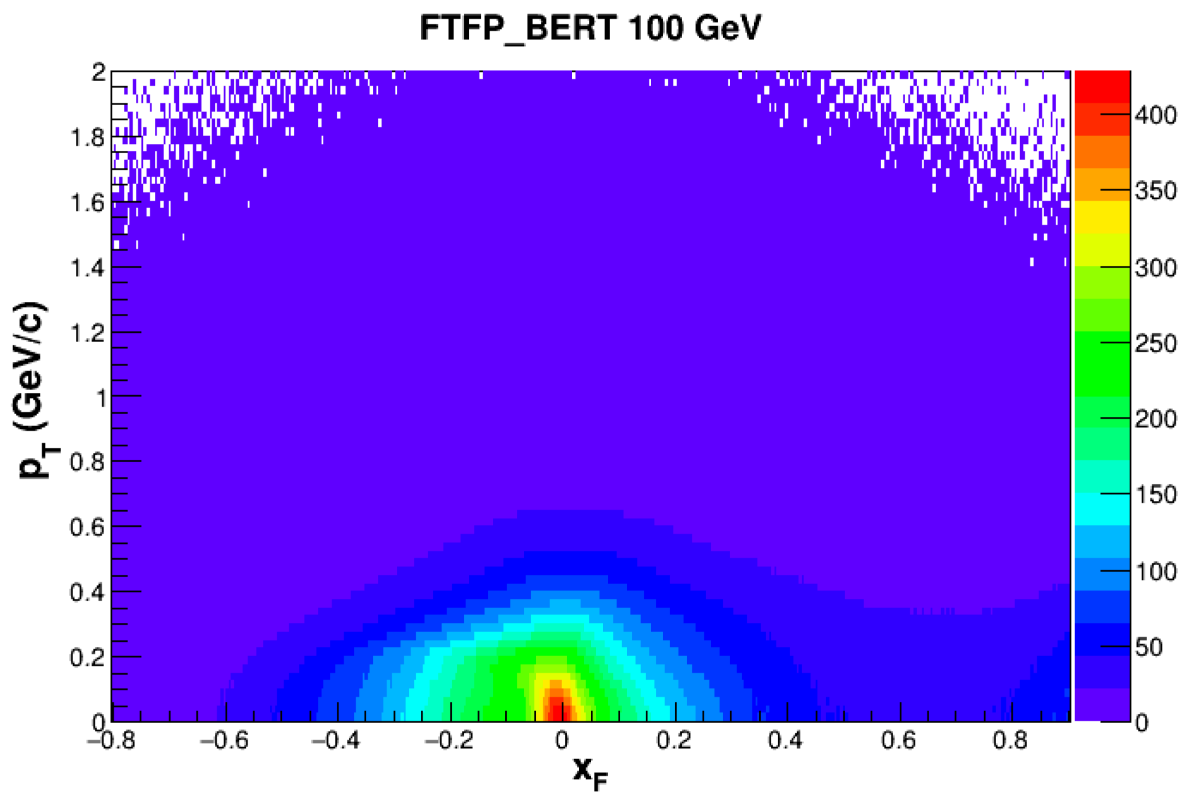
Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 55 GeV

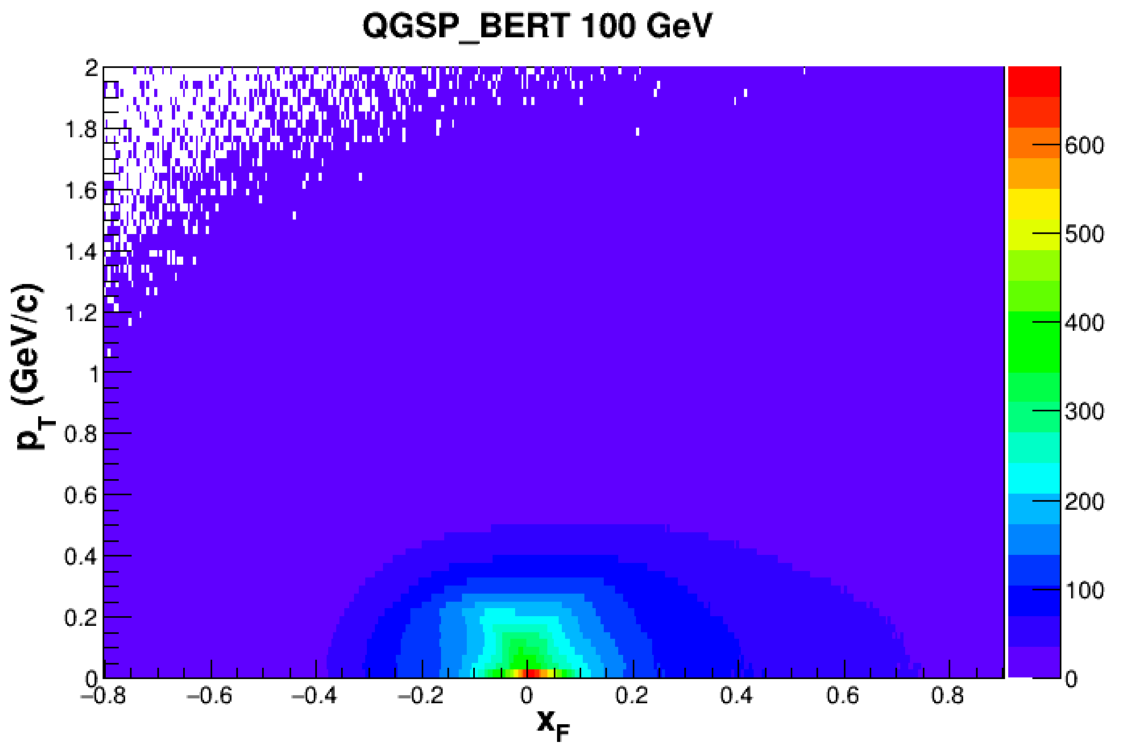


Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 60 GeV

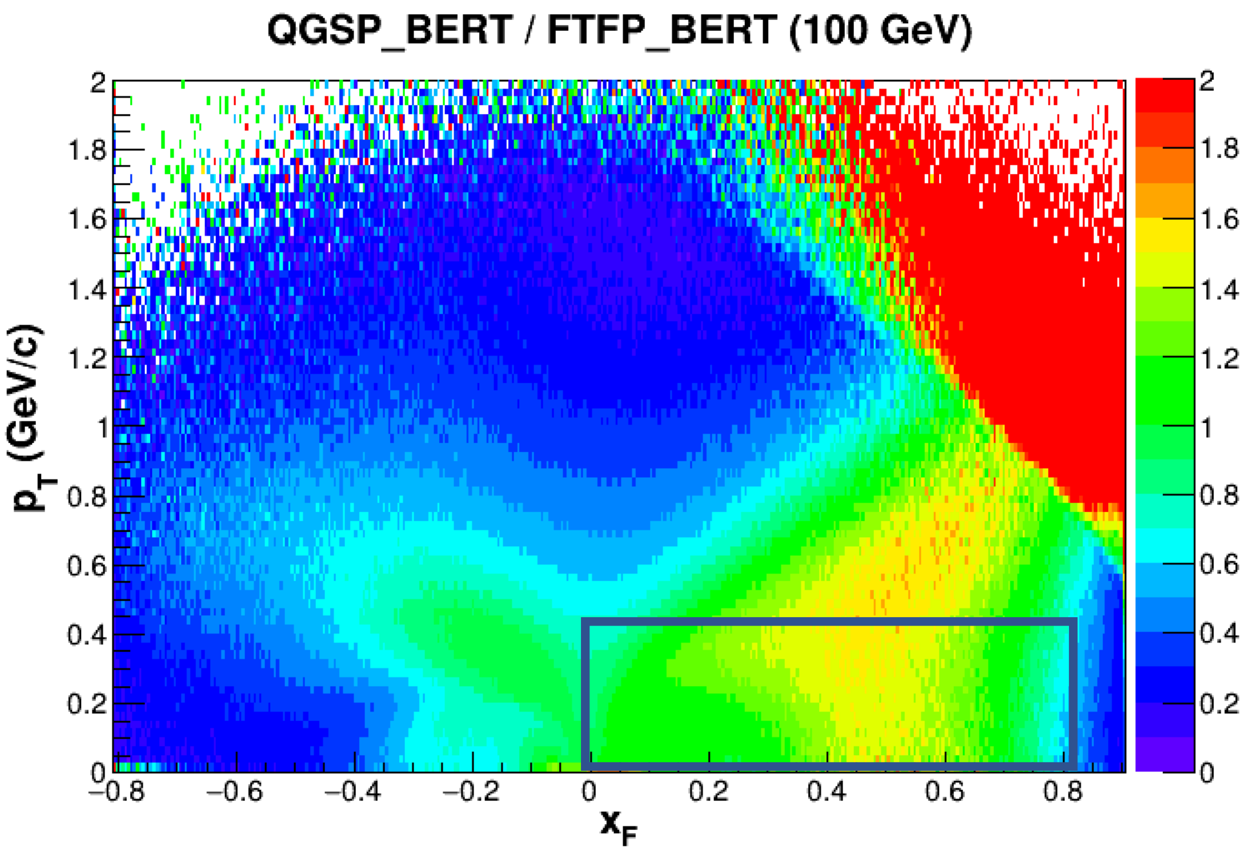


Invariant cross-section for FTFP_BERT and QGSP_BERT for $\boxed{100\ GeV}$

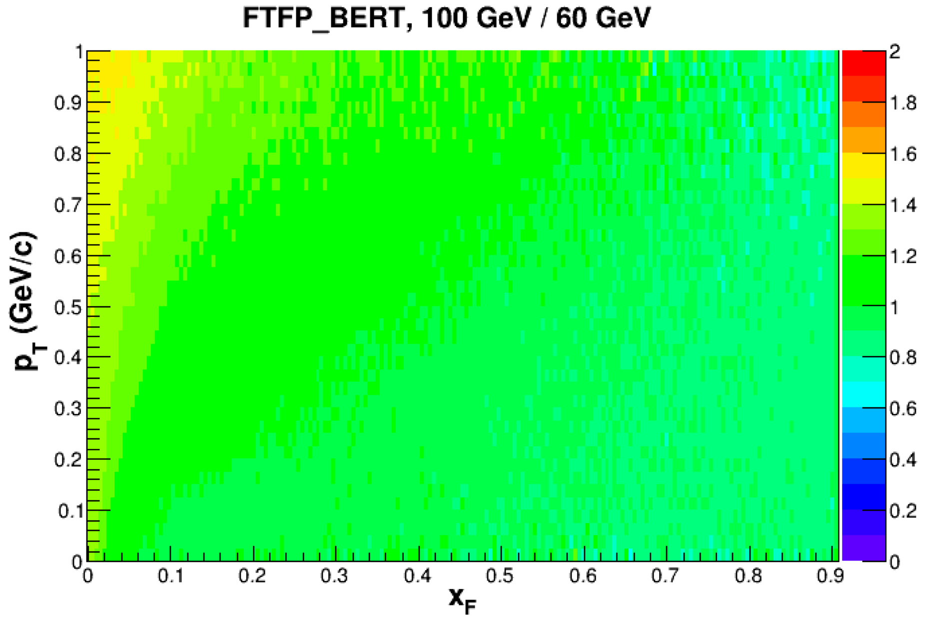


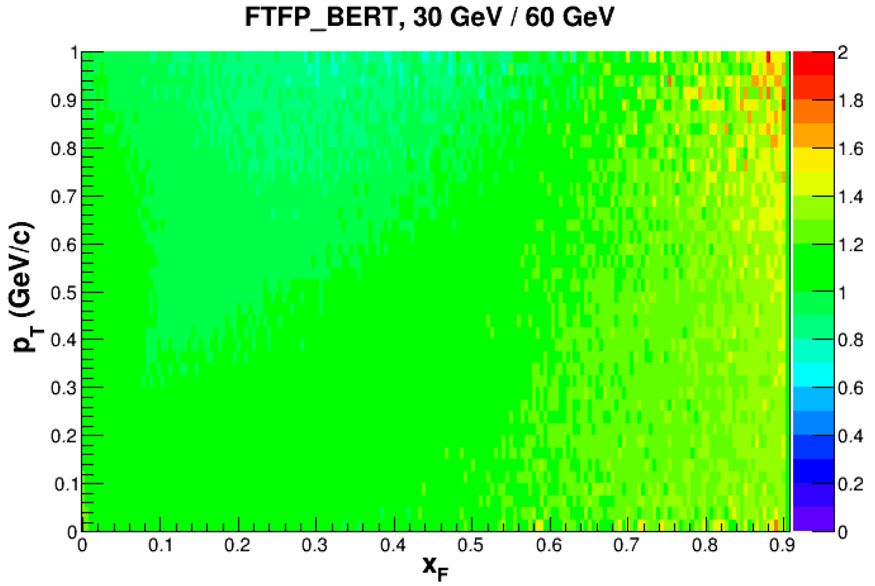


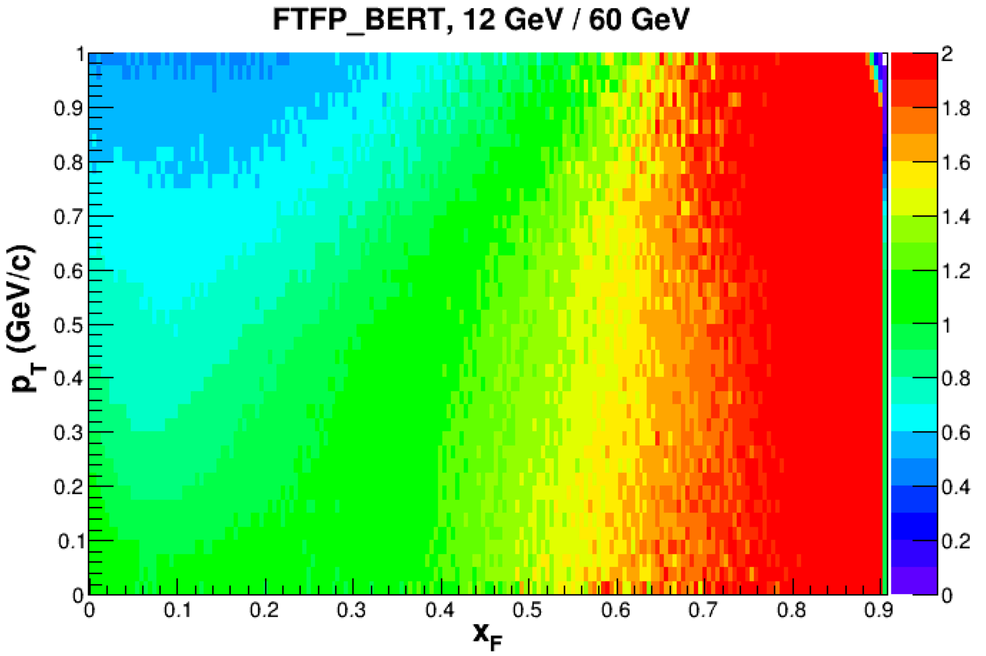
Invariant cross-section ratio for QGSP_BERT and FTFP_BERT for 100 GeV



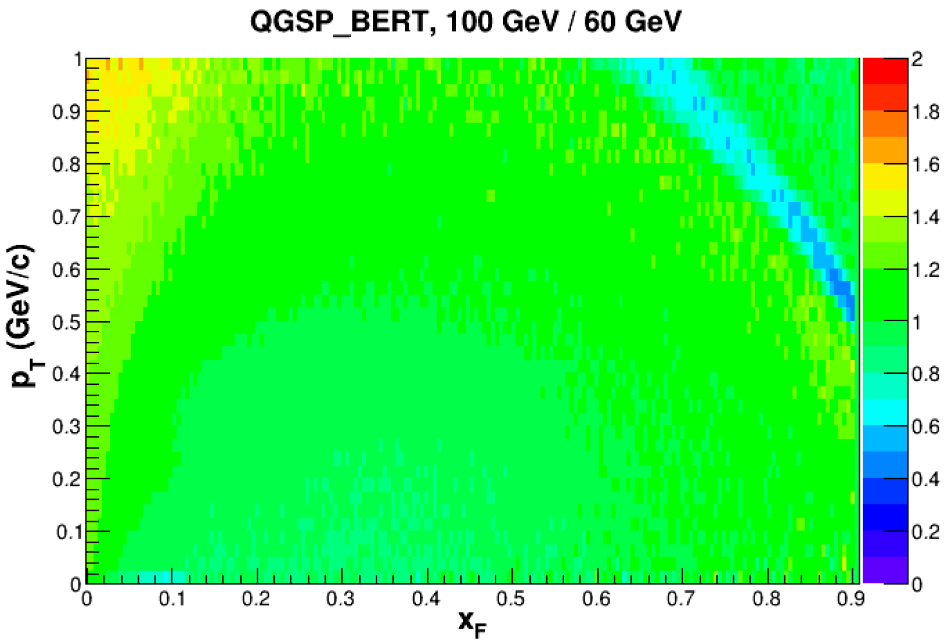
Invariant cross-section comparison by using FTFP_BERT

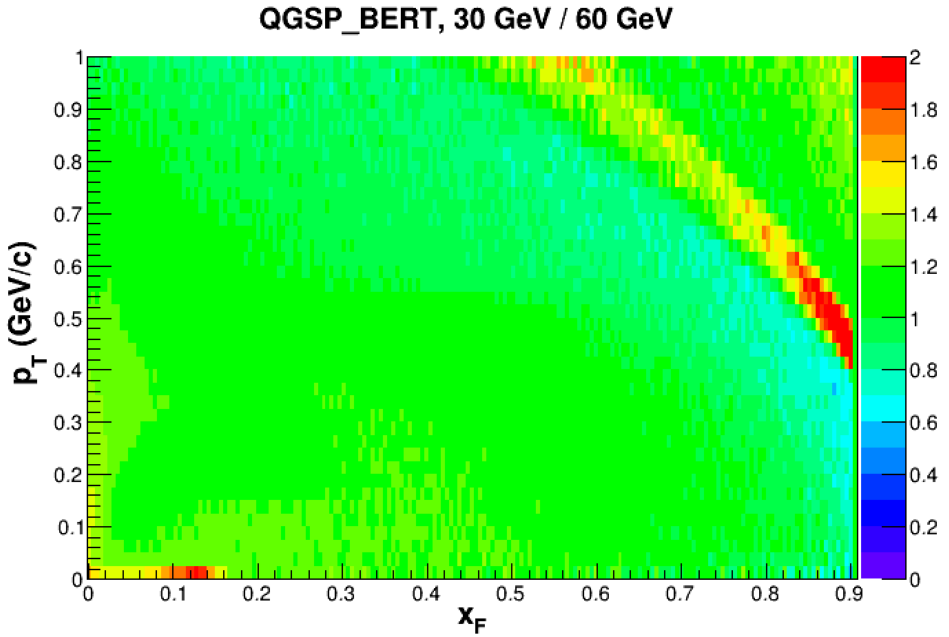


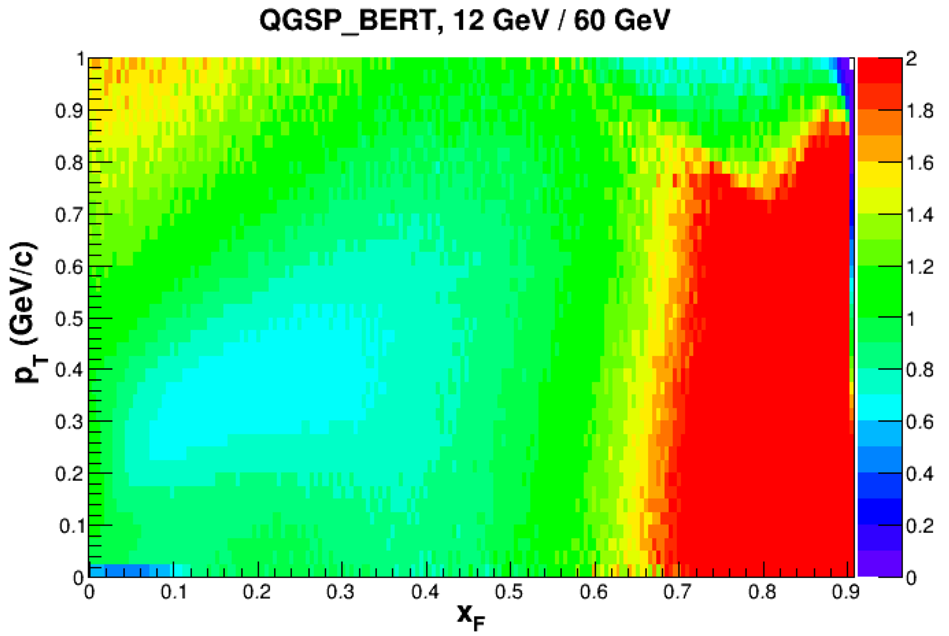




Invariant cross-section comparison by using QGSP_BERT







Grid statistics

Cluster	42154795@jobsub02.fnal.gov
Number of Jobs	500
Submitted	2021-02-19 00:42:17 +0000 UTC
Owner/Group	nbostan / dune (nbostan@FNAL.GOV)
Command	g4hp_job.sh
Requested Memory	1200 MiB
Requested Disk	35.0 GiB
Expected Wall Time	23h40m0s

View this cluster on Fifemon

Average time waiting in queue: 5m20s

Success rate (% jobs with exit code 0): 100.0%

Used	**Min**	**Max**	**Avg**
Memory	394.3 MiB	480.1 MiB	464.2 MiB
Disk	0.0 GiB	0.0 GiB	0.0 GiB
Wall Time	3m57s	16m0s	8m22s
CPU Time	3m34s	14m31s	7m23s

Efficiency	**Min**	**Max**	**Avg**
Memory	33.6%	41.0%	39.6%
Disk	0.0%	0.0%	0.0%
CPU	52.8%	97.7%	88.3%
Time	0.3%	1.1%	0.6%

Exit Code	**# Jobs**
0	500

Each job has 10M incident particles

The center of momentum energy can be calculated with the mass of the incoming particle, the mass of the target nucleon involved in the collision and the incoming beam energy:

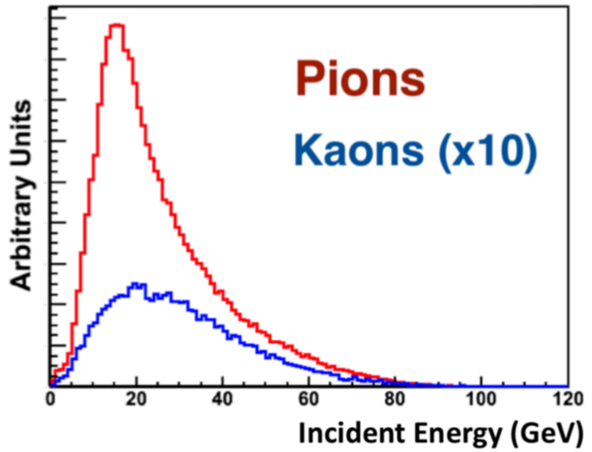
$$E^{CM} = \sqrt{m_{inc}^2 + m_{nucleon}^2 + 2E_{inc}m_{nucleon}}$$

```
(*for Barton et al, 100 GeV*)
√((0.139)^2 + (0.938)^2 + 2*0.938*100)
Out[1]= 13.7295

(*for NA61, 60 GeV*)
In[2]:= √((0.139)^2 + (0.938)^2 + 2*0.938*60)
Out[2]= 10.6517

(*for HARP, 12 GeV*)
In[3]:= √((0.139)^2 + (0.938)^2 + 2*0.938*12)
Out[3]= 4.83851
```

These values show the Ecm values for Barton, NA61 and HARP.

- ✓ Feynman-x works better for Ecm >10 GeV (the scaling)

Incident meson interaction in NuMI.



Definitions:

Measurements of bin-integrated cross sections of charged-pion produced in proton-carbon interactions at 31 GeV were released in [4]. The bin are in terms of the momentum (P) and the angle (θ) with respect to the beam direction. The results are $g = \frac{1}{\Delta P}\sigma(p,\theta)$ and they can be related to the invariant cross section:

$$g = \frac{1}{\Delta P}\int\int\int d^3\sigma$$
$$= \frac{1}{\Delta P}\int\int\int\left[\frac{1}{E}\right]\underbrace{\left[E\frac{d^3\sigma}{dp^3}\right]}_{f} dp^3. \qquad (9)$$

The bin content g of $[P_{low}, P_{high}]$ and $[\theta_{low}, \theta_{high}]$ divided by the P bin size is:

$$g([P_{low}, P_{high}], [\theta_{low}, \theta_{high}]) = \frac{1}{\Delta P}\int_{P_{low}}^{P_{high}}\int_{\theta_{low}}^{\theta_{high}}\int_0^{2\pi}\frac{1}{E}f(x_F, p_T)p^2 sin\theta dp d\theta d\phi. \qquad (10)$$

The average invariant differential cross section, $< f >$, weighted by the inverse energy of the outgoing particle in the interaction is given by:

$$\langle f(x_F, p_T)\rangle = \frac{\int_{P_{low}}^{P_{high}}\int_{\theta_{low}}^{\theta_{high}}\int_0^{2\pi}\frac{1}{E}f(x_F, p_T)p^2\sin\theta dp d\theta d\phi}{\int_{P_{low}}^{P_{high}}\int_{\theta_{low}}^{\theta_{high}}\int_0^{2\pi}\frac{1}{E}p^2\sin\theta dp d\theta d\phi}. \qquad (11)$$

The denominator (D) in Eq. 11 is

$$D = 2\pi\left[\cos\theta_{low} - \cos\theta_{high}\right]\left[\frac{p}{2}\sqrt{p^2+m^2} - \frac{m^2}{2}log\left(\sqrt{p^2+m^2}+p\right)\right]_{P_{low}}^{P_{high}}. \qquad (12)$$

And then the $< f >$ can be calculated from the bin content as:

$$\langle f(x_F, p_T)\rangle = \frac{\Delta P g([P_{low}, P_{high}], [\theta_{low}, \theta_{high}])}{D}. \qquad (13)$$

$\pi^+ C \to \pi^\pm X$

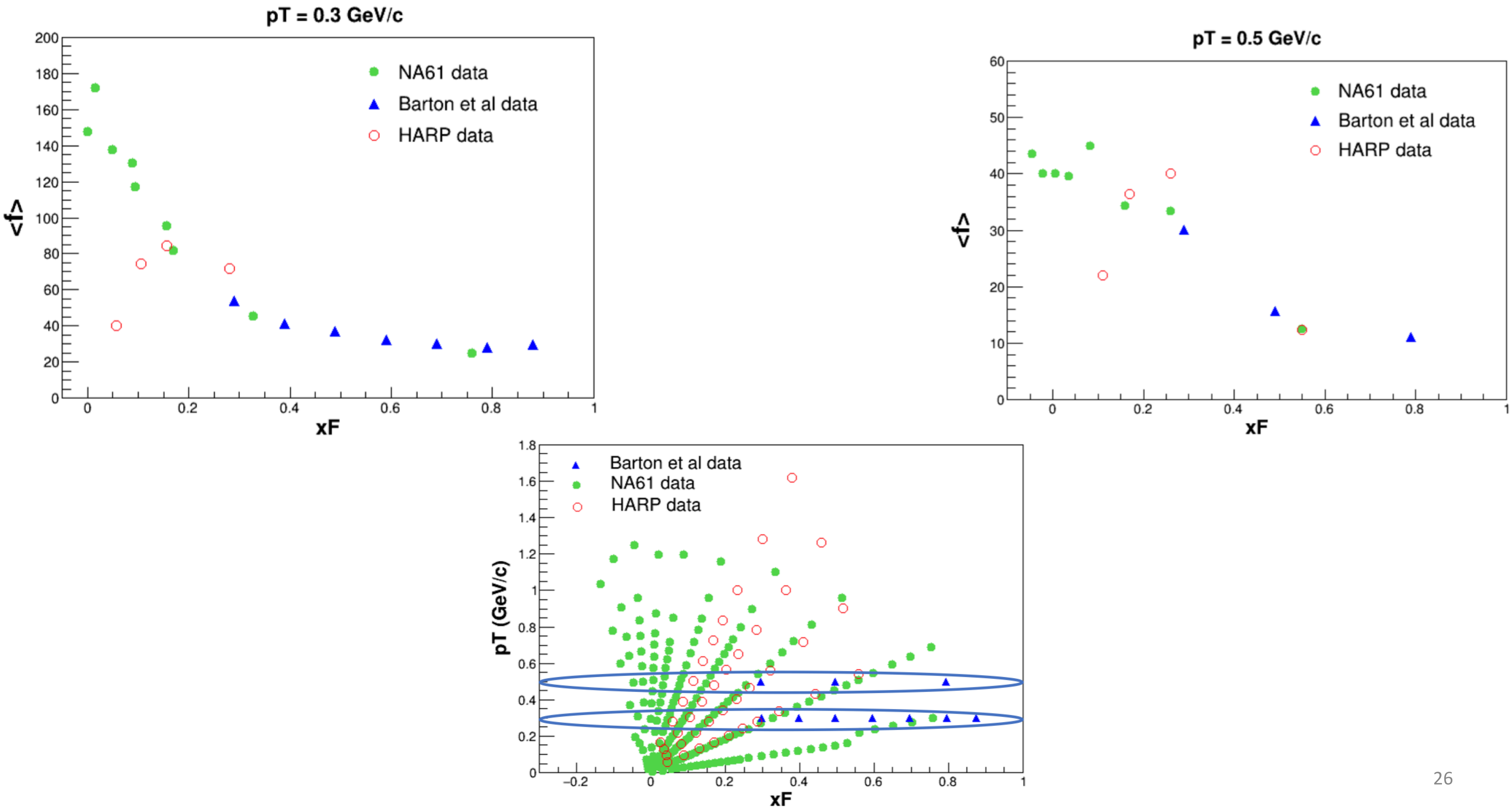
NA61 recently published integrated multiplicities of different particles in pion-carbon interactions at 60 GeV in terms of the P and θ with respect to the beam direction [6]. The results are s $k = \frac{1}{\Delta P\Delta\theta}n(p,\theta)$ can be related to the invariant cross section by using the production cross section (σ_{prod}), also measured in the paper:

$$k = \frac{1}{\Delta P\Delta\theta}\int\int\int d^3n$$
$$= \frac{1}{\Delta P\Delta\theta\sigma_{prod}}\int\int\int\left[\frac{1}{E}\right]\underbrace{[\sigma_{prod}]\left[E\frac{d^3n}{dp^3}\right]}_{f} dp^3. \qquad (15)$$

And then:

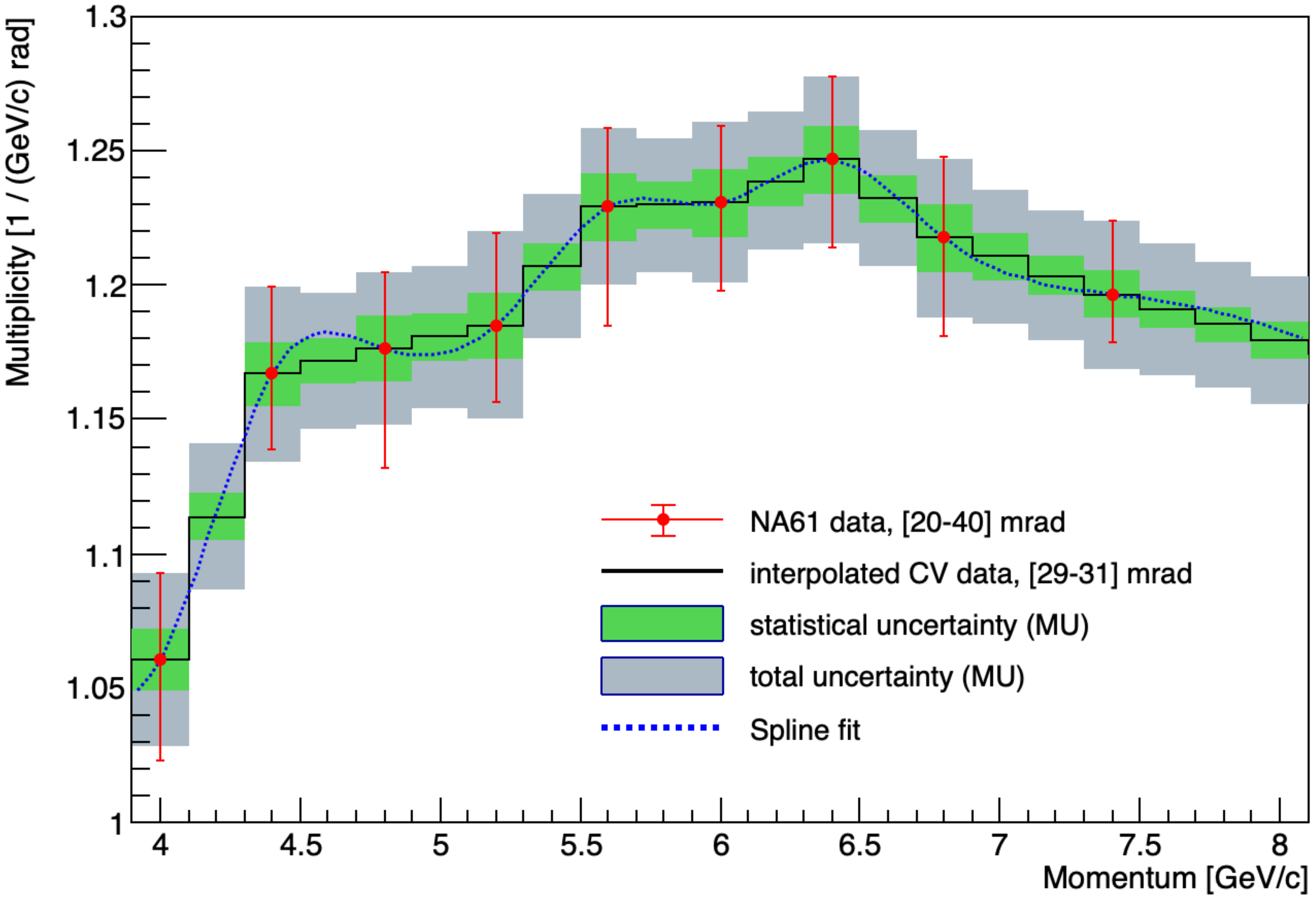
$$\boxed{\langle f(x_F, p_T)\rangle = \frac{\Delta P\Delta\theta\sigma_{prod}k([P_{low}, P_{high}], [\theta_{low}, \theta_{high}])}{D}.} \qquad (16)$$

Invariant cross-section and xF comparisons for different datasets:



Interpolation of NA61 data for 20-40 mrad:

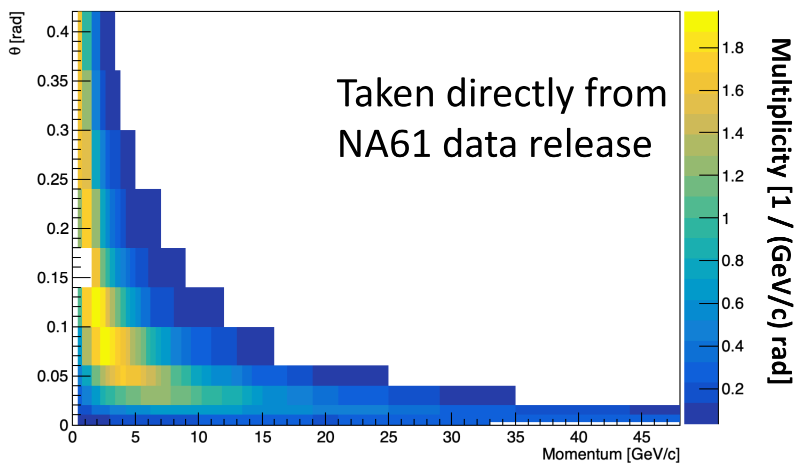
Same plot as in doc-21627.
But this plot includes
improved binning:



Reminder

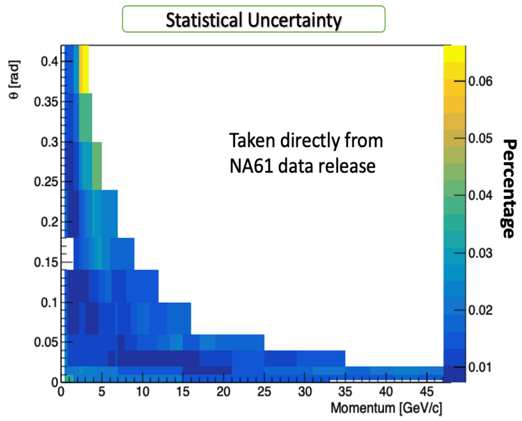
Data central value

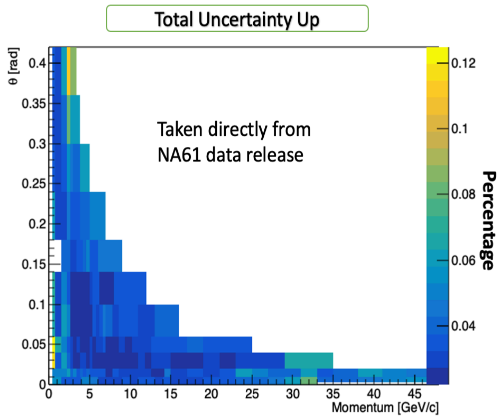
- The central value comes in TH2Poly bins of (θ, P). For instance for the same momentum bin we can have different θ ranges:



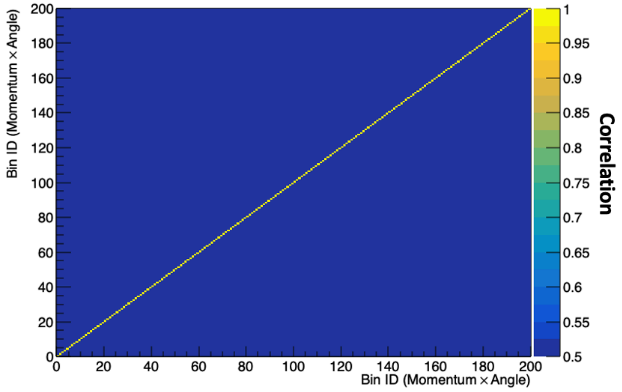
- For statistical uncertainties, random shifts in uncorrelated bins, Gaussian distributed and using the statistical uncertainty, are generated creating new data in 5000 universes in total. We interpolate in each universe.

Data uncertainties: Statistical uncertainty (left), Total uncertainty "Up" (Systematics Up and statistical added in quadrature)





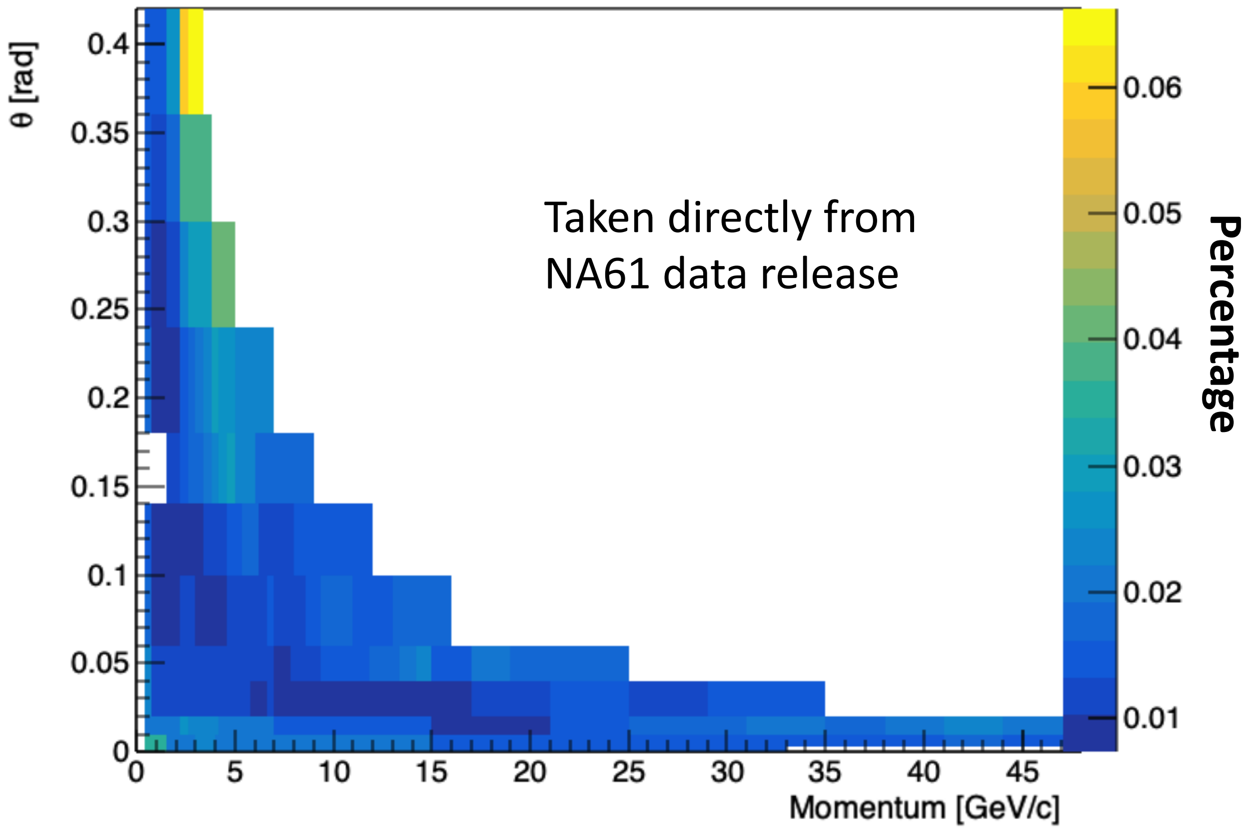
- For systematic uncertainties, the bin-to-bin correlation is not published by NA61. The data release split in systematics coming from different sources and we use **+50% correlation** across all bins as a first attempt.



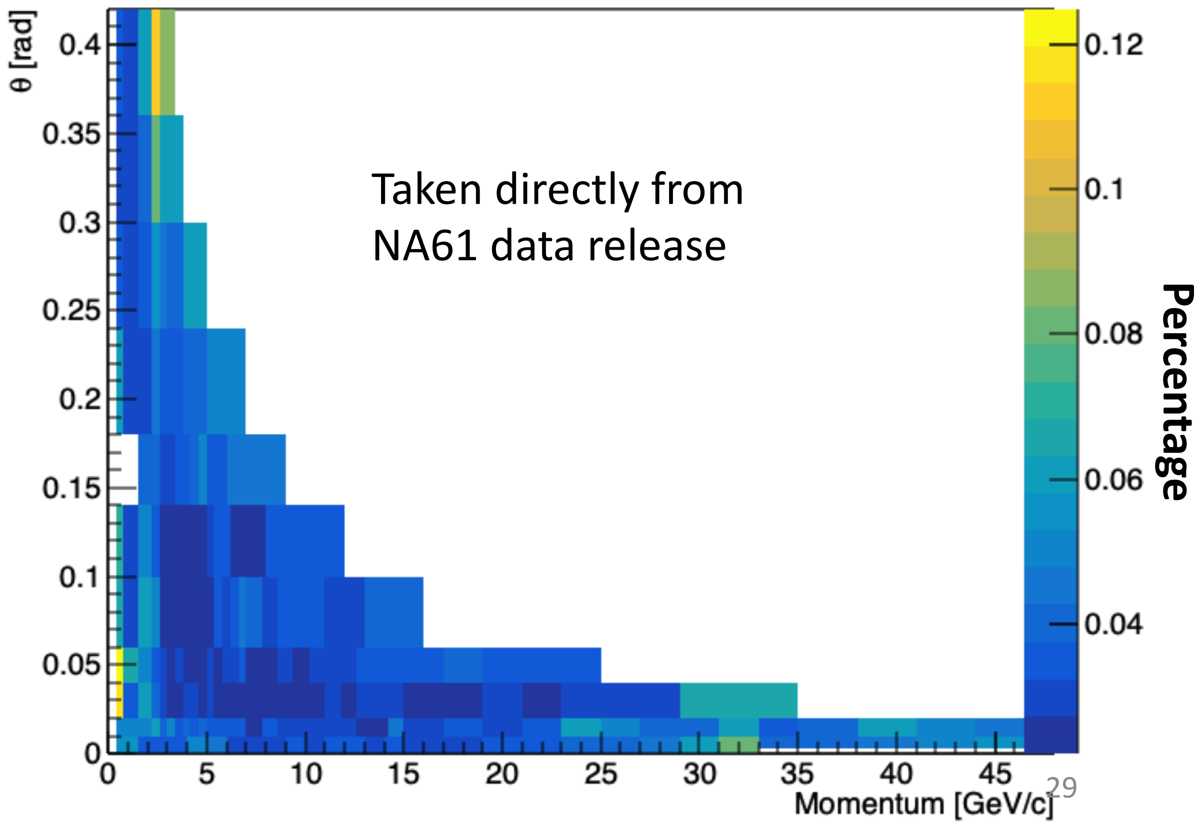
Data uncertainties

- Uncertainties are shown below:
  - Statistical uncertainty (left)
  - Total uncertainty "Up" (Systematics Up and statistical added in quadrature)

Statistical Uncertainty



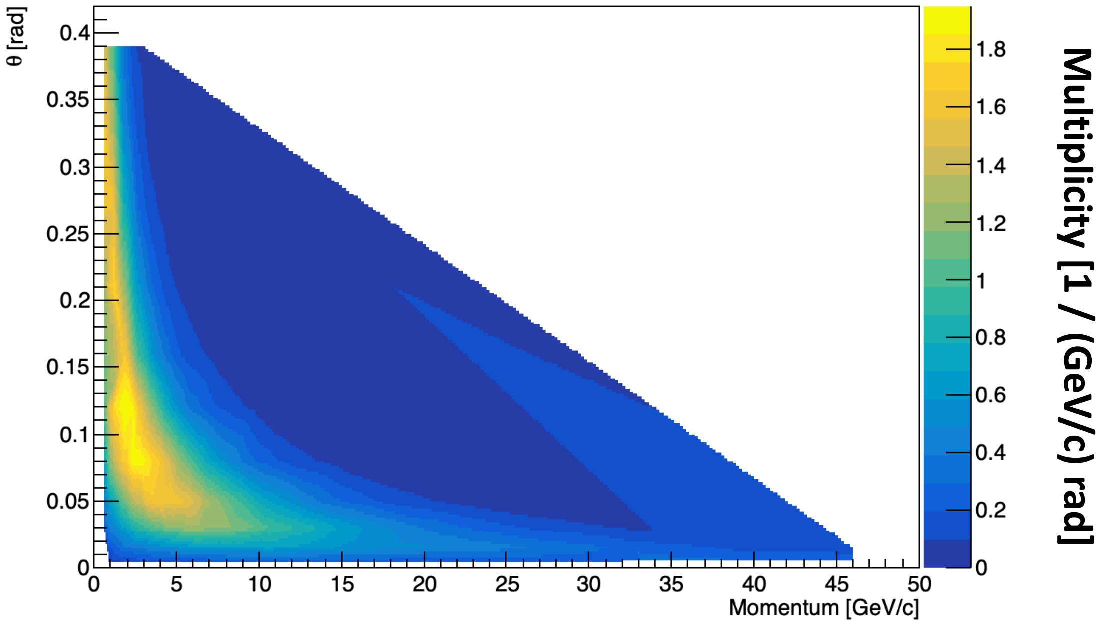
Total Uncertainty Up



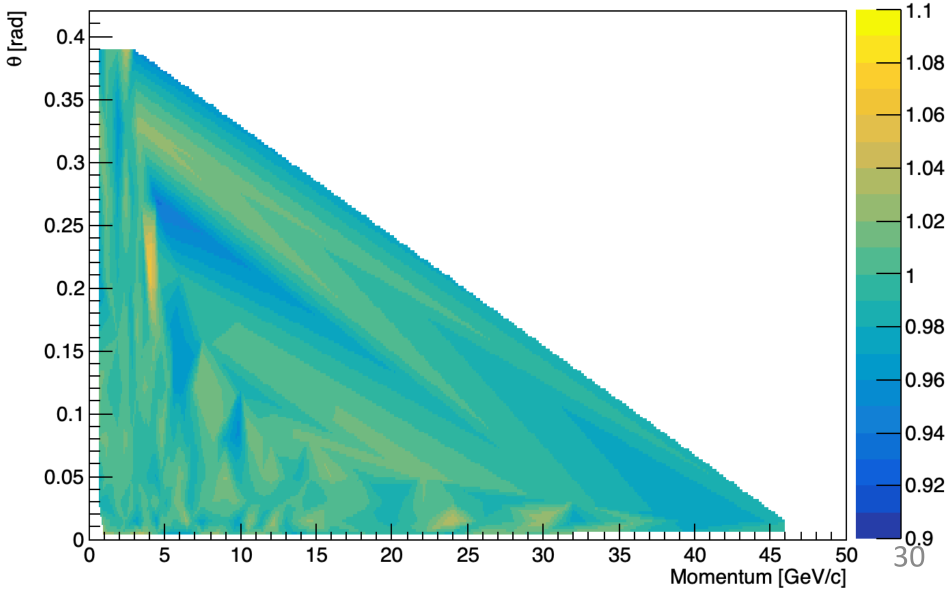
Statistical uncertainties

- We are treated the NA61 statistical and systematic uncertainties independently.
- Random shifts in uncorrelated bins, gaussian distributed and using the statistical uncertainty, are generated creating new data in 5000 universes in total. We interpolate in each universe.
- For instance, for the new data in universe 10:

New CV in universe 10



Ratio of the new CV over the nominal

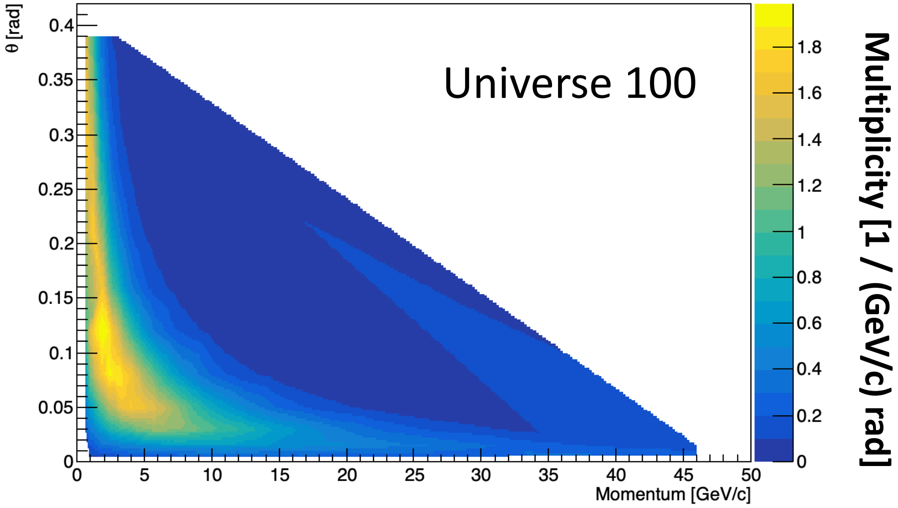


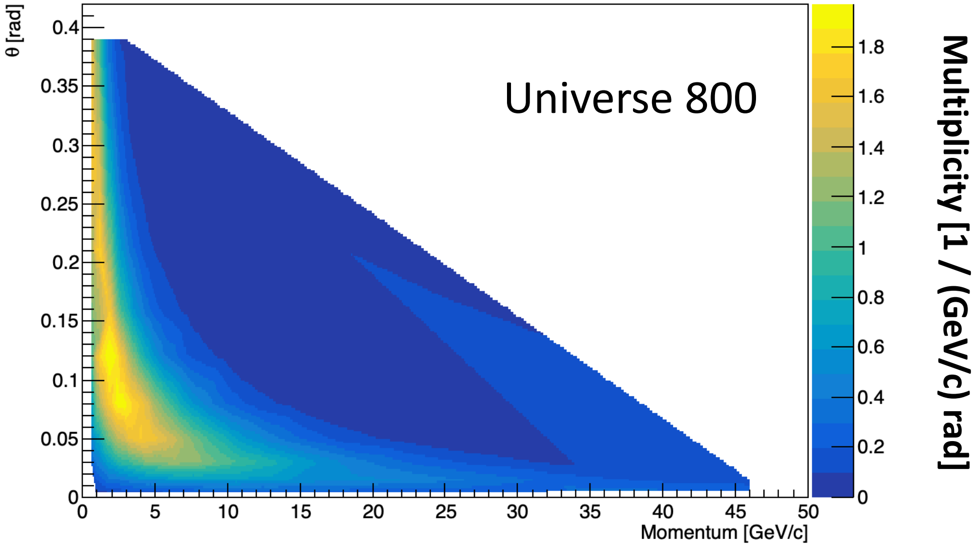
Ratio for Universe 10 to CV

Statistical uncertainties

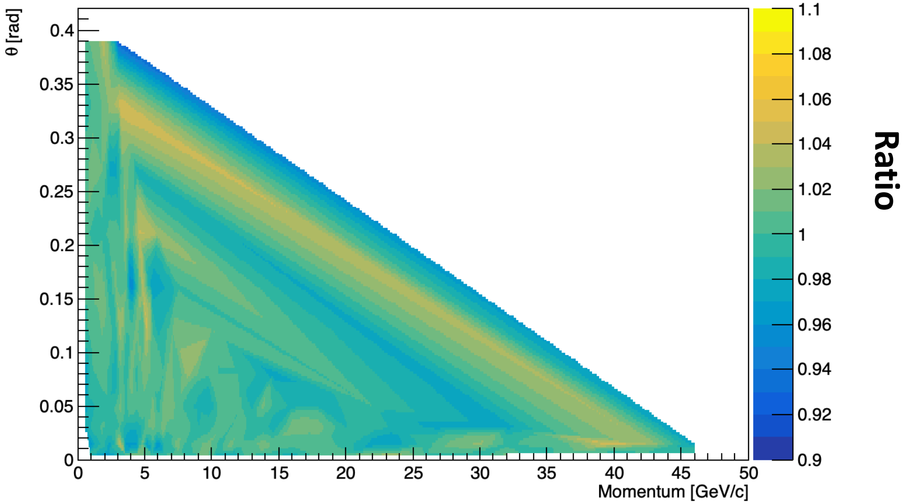
- Other examples:

New CV

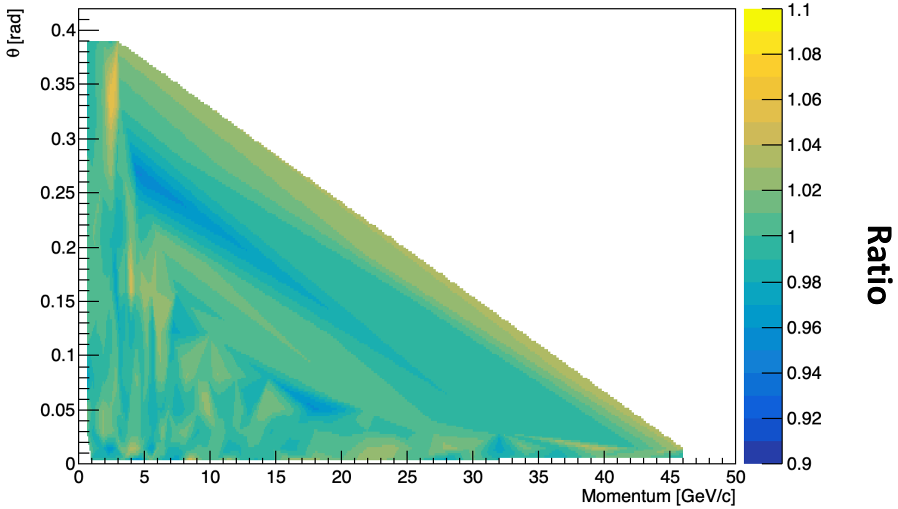




Ratio of the new CV over the nominal



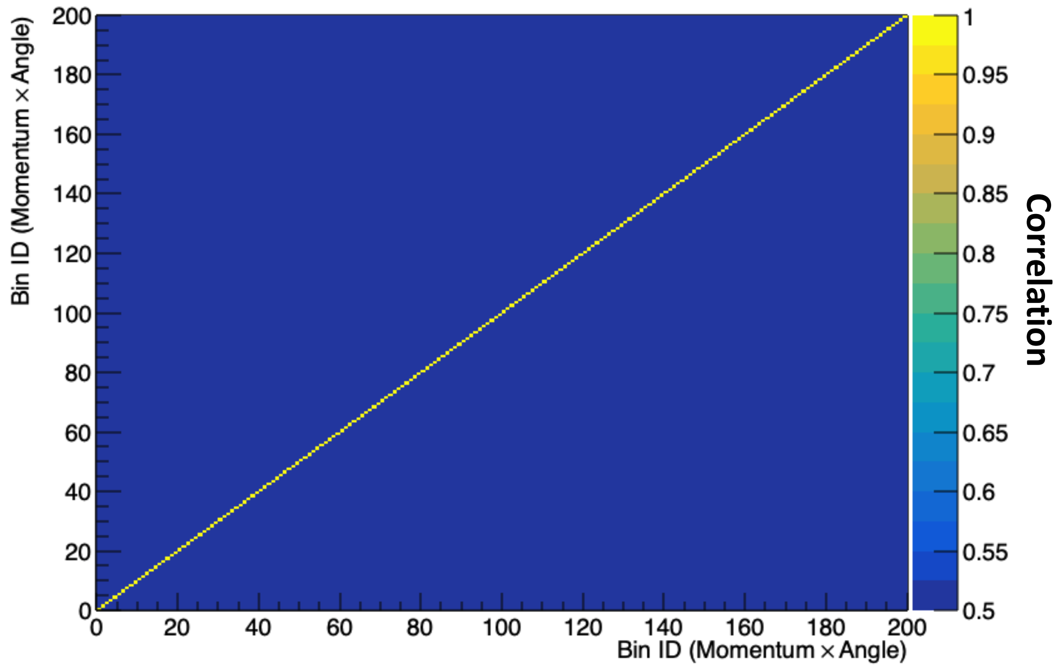
Ratio for Universe 100 to CV

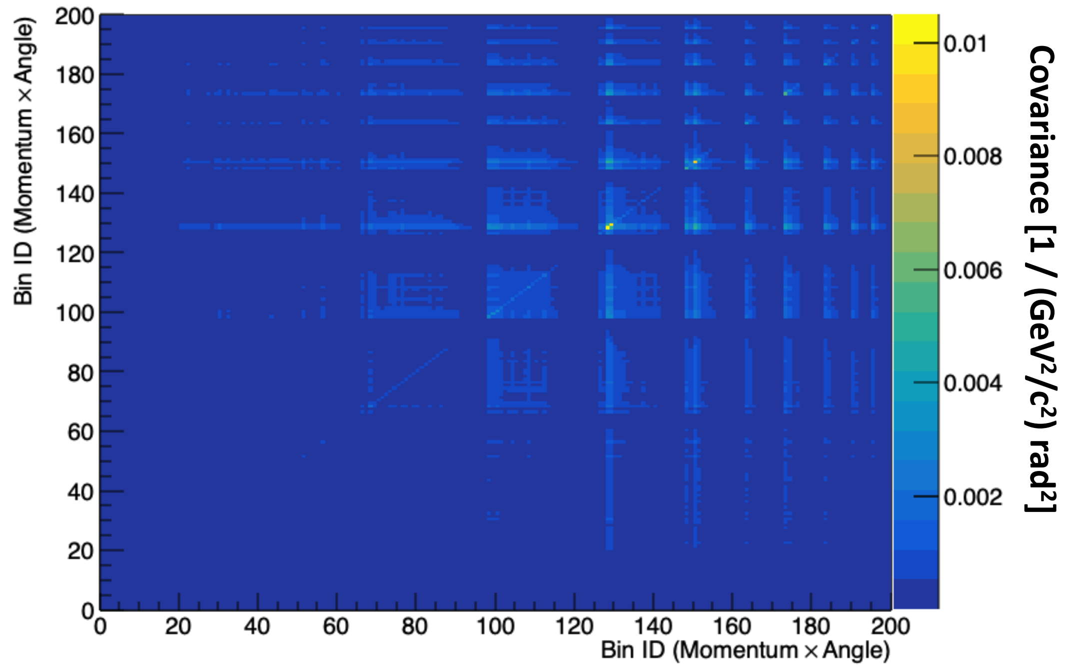


Ratio for Universe 800 to CV

Systematic uncertainties

- The bin-to-bin correlation is not published by NA61. The data release split in systematics coming from different sources.
- We use +50% correlation across all bins as a first attempt (we want to have the infrastructure when we have better values).





- 200 data we have for NA61 in total